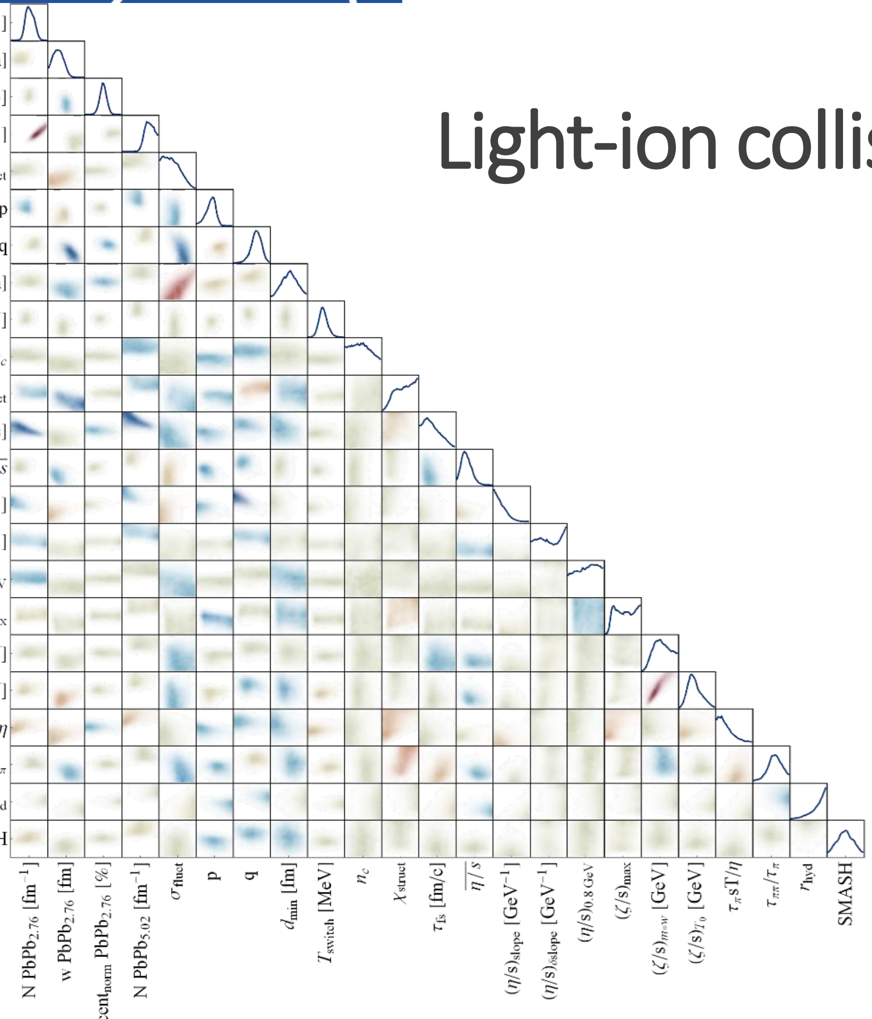
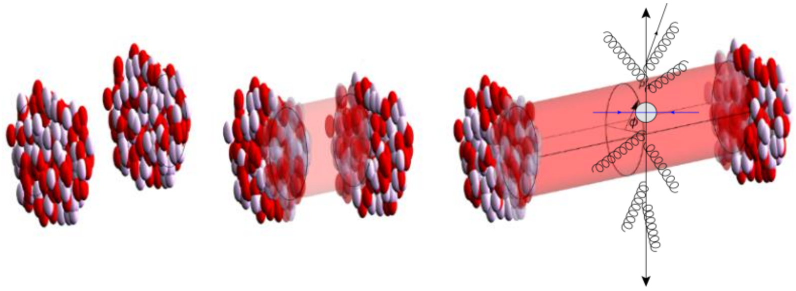


Light-ion collisions as a laboratory for effective theories of nuclei

Towards precision physics with global analyses

2112.13771, 2206.13522 (PRL) and to appear with Govert Nijs and Giuliano Giacalone



Wilke van der Schee
INT, Seattle

15 February 2023

Outline

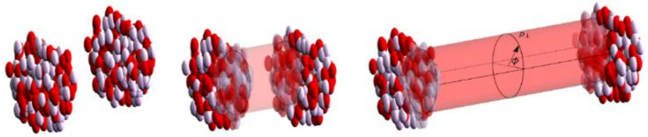
Heavy ion collisions and a global analysis

- Estimate many (physical) parameters using a lot of experimental data
- Recent lessons on the shape of nucleons inside a nucleus
- In particular: the PbPb total cross section and the nucleon width

Nuclear structure and the shape of nuclei

- Heavy ion collisions as a collapsing wave function in nuclear structure
- New results from LHC soon? (oxygen)
- **A systematic analysis of Oxygen and Neon**

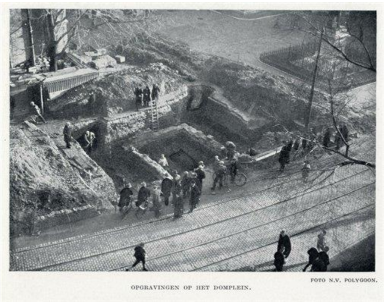
Standard model of heavy ion collisions



(# parameters)

Trajectum

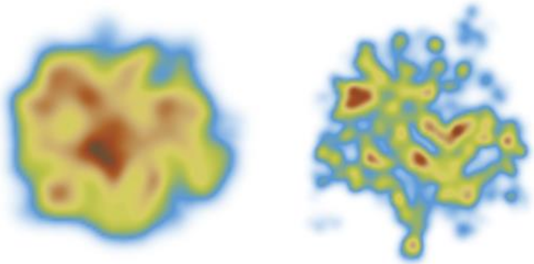
- New public heavy ion code
- Originally Utrecht (now MIT/CERN)
- Fast
- Precise (all cuts equal to experiment)
- Scalable



Roman excavations in **Utrecht** in 1929

Initial stage (11)

Subnucleonic structure? (8)

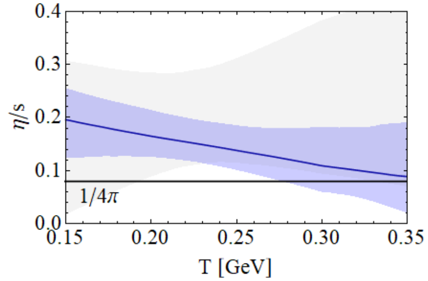


Non-thermal flow? (2)
with hydrodynamised initial stage

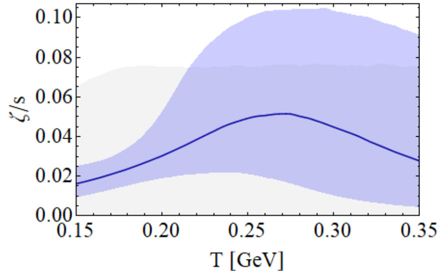
Fluctuations? (1)

Viscous hydrodynamics (9)

Shear viscosity (4)

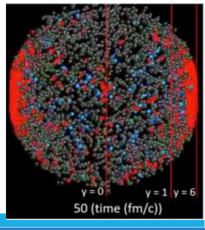


Bulk viscosity (3)

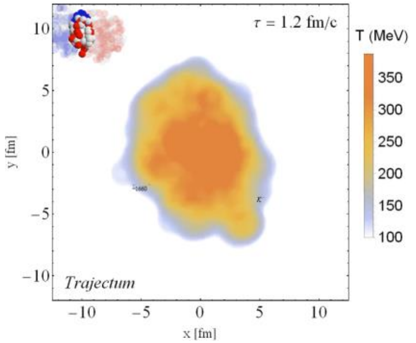


Second order transports: 2

Cascade of hadrons (1)



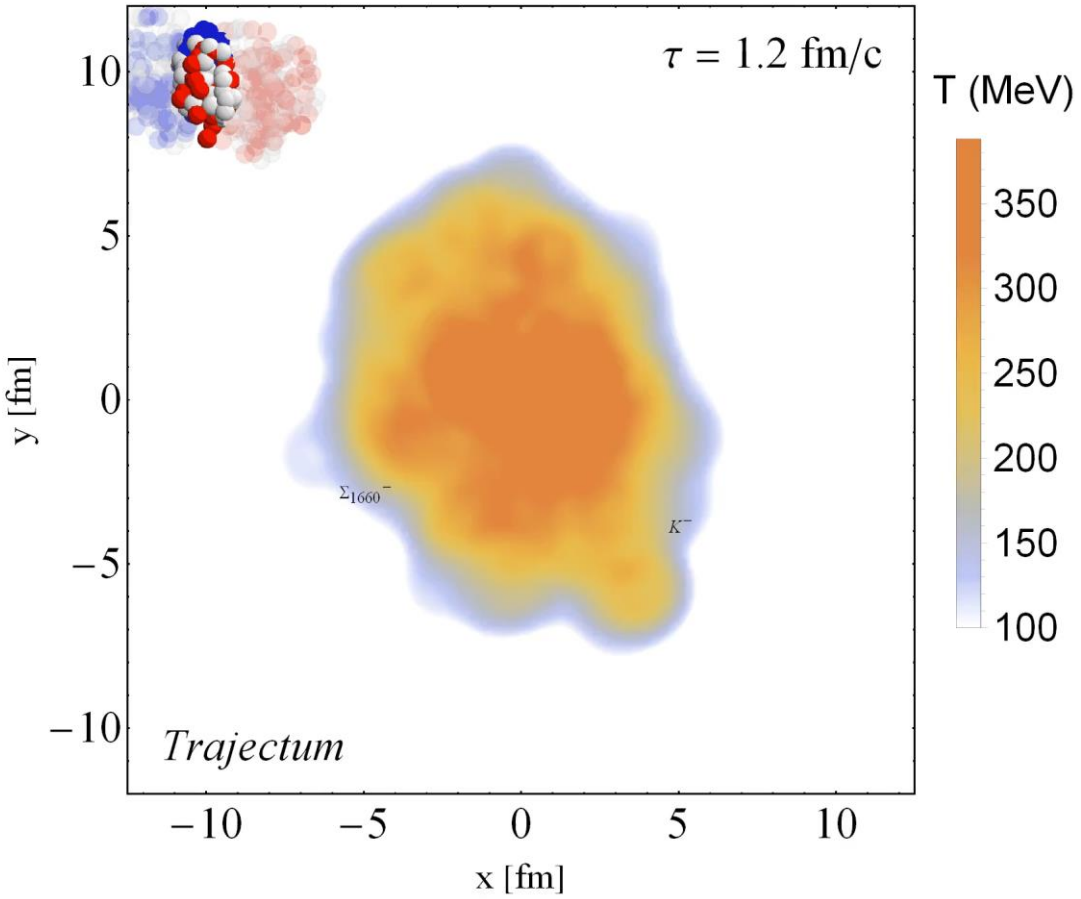
Jonah Bernhard, Scott Moreland and Steffen Bass, Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma (2019)
Govert Nijs, WS, Umut Gursoy and Raimond Snellings, A Bayesian analysis of Heavy Ion Collisions with Trajectum (2020)



Trajectum

1. Quite straightforward to use (see param file, right)

2. Includes analyse routine
   - Parallelised: can analyse unlimited number of events

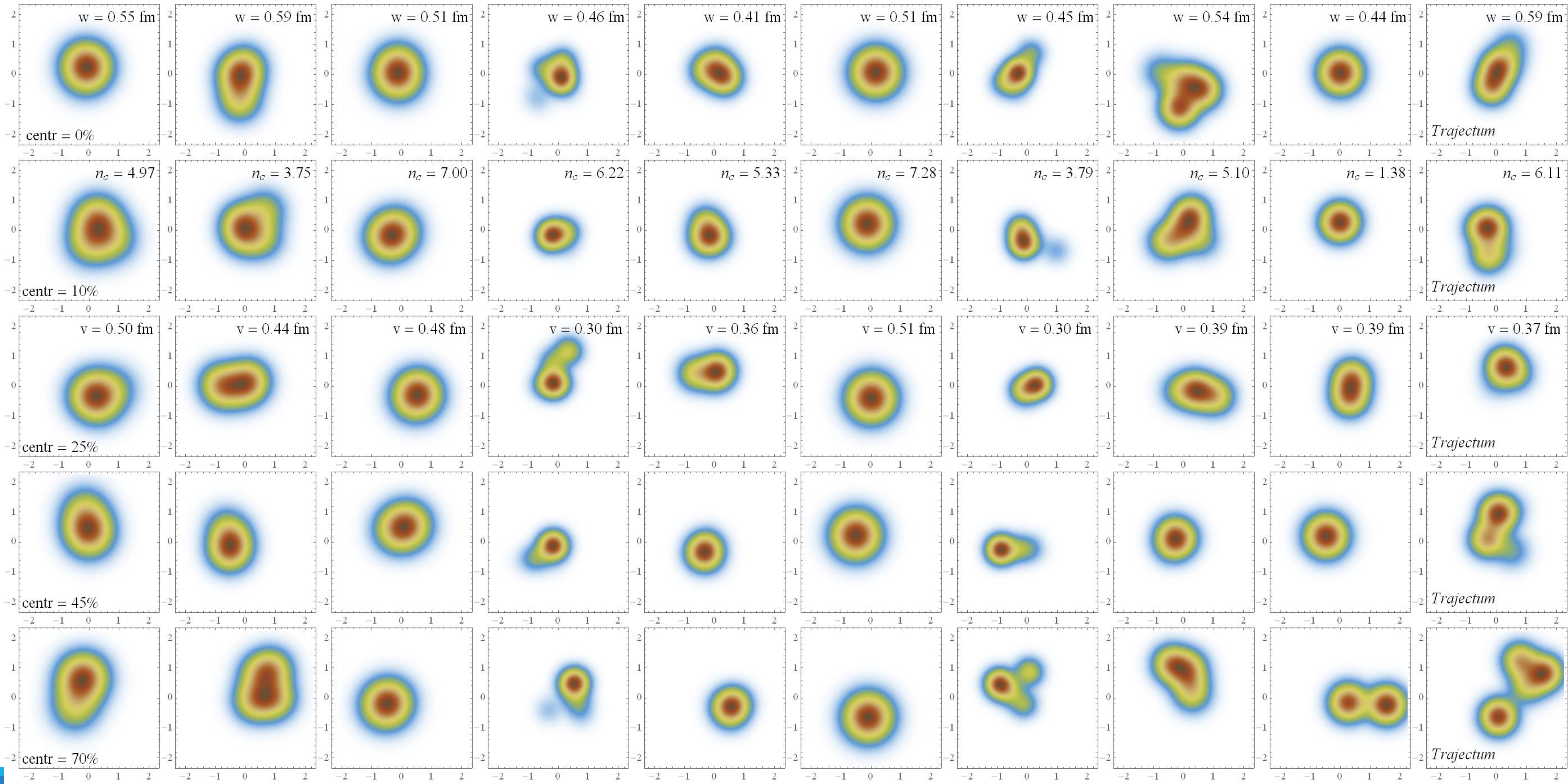



```
general{
    output=out
    format=smash
    f0500=false
    numevents=1
    seed=7398984.747399307
    debugoutput=true
    numthreads=2
}

entropyacceptanceprobability{
    0:0.0
    24:0.0
    24.5:0.05
    25.5:0.05
    26:0.0
    100:0.0
}

trentosubstructurePbPb{
    dmin=0.63933
    w=0.701919
    sigmann=70.0
    sigmafluct=0.73579
    p=0.14388
    q=1.0
    Eref=0.2
    norm=23.507
    freestreamingreferencetime=1.17085
    freestreamingvelocity=0.62672
    weaktostrong=0.0
    nref=20
    alpha=0
    nc=3.2747
    voverw=0.4892041602706295
}

secondorderhydro{
    numlatticesites=166.0
    latticesize=33.2
}

musclsolverktminmodfastmidpoint{
    cflconstant=0.08
}

LatticeEOStempdepDuke{
    shearhrg=0.0895066
    shearmin=0.0895066
    shearslope=0.43252
    shearcrv=0.231195
    shearrelaxationtime=6.318855
    bulkmax=0.0030138
    bulkT0=0.21471
    bulkwidth=0.10906
    bulkrelaxationtime=0.0687
    deltapipiovertaupi=1.33333333333333
    phi7overpressure=0.128571
    taupipiovertaupi=1.61033
    lambdapiPiovertaupi=1.2
    deltaPiPiovertauPi=0.66666666666666
    lambdaPipiovertauPi=1.6
    phi1overpressure=0
    phi3overpressure=0
    phi6overpressure=0
}

cooperfryehadronizer{
    freezeouttemp=153.456
    rapidityrange=0.1
}
```

Thickness function nucleon

Ten different probable parameter settings →

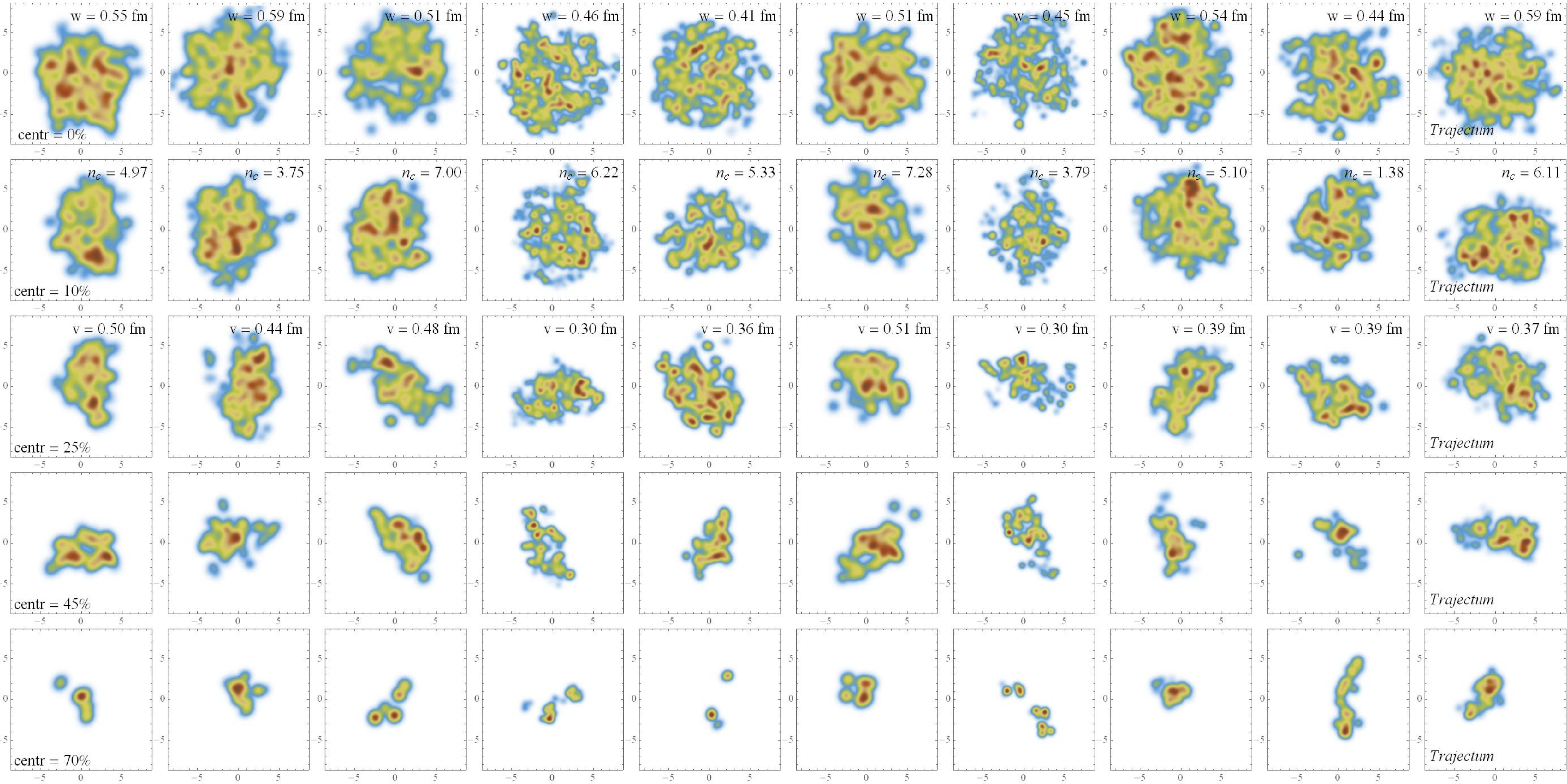
Configurations ↓



Ten different probable parameter settings →

Thickness function Pb

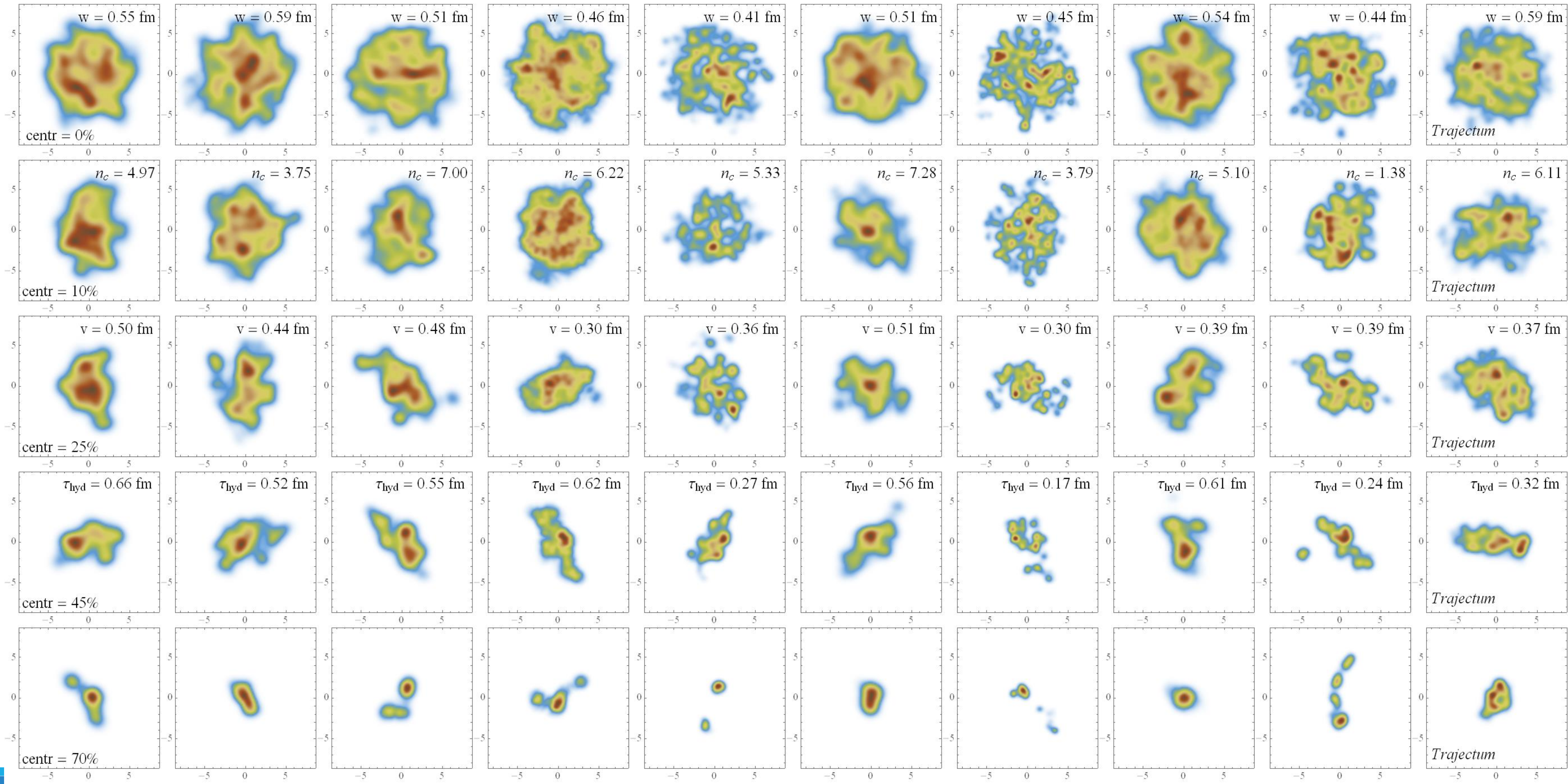
Centrality →



Ten different probable parameter settings →

Energy density function Pb

Centrality →



Performing a global analysis

Bayes theorem:

$$\mathcal{P}(\boldsymbol{x}|\mathbf{y}_{\exp}) = \frac{e^{-\Delta^2/2}}{\sqrt{(2\pi)^n \det(\Sigma(\boldsymbol{x}))}}\mathcal{P}(\boldsymbol{x})$$

with $\Delta^2 = (\mathbf{y}(\boldsymbol{x}) - \mathbf{y}_{\exp}) \cdot \Sigma(\boldsymbol{x})^{-1} \cdot (\mathbf{y}(\boldsymbol{x}) - \mathbf{y}_{\exp})$

Model depends on parameters non-linearly

- Run model on 1200 `design' points
- Use an emulator for any point in parameter space (**GP**)

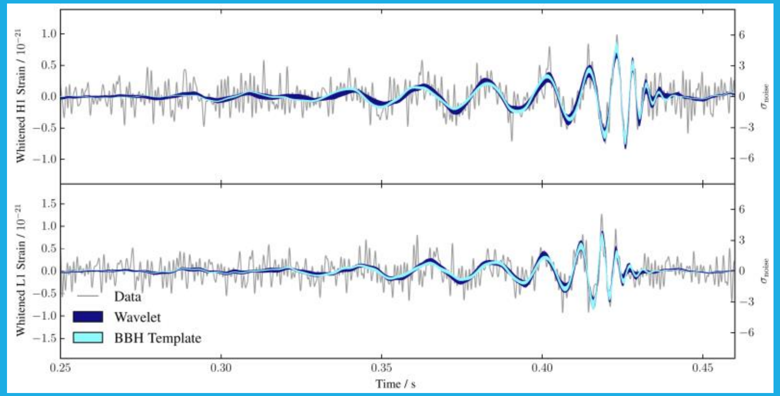
Markov Chain Monte Carlo

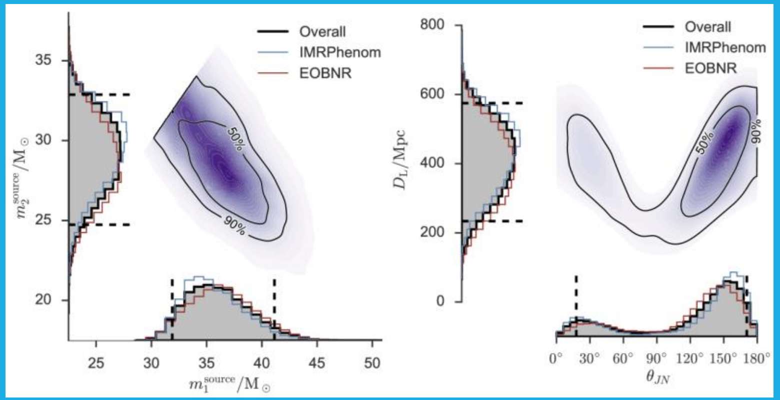
- 653 data points
- Obtain posterior probability density of parameters

Compare posterior with data

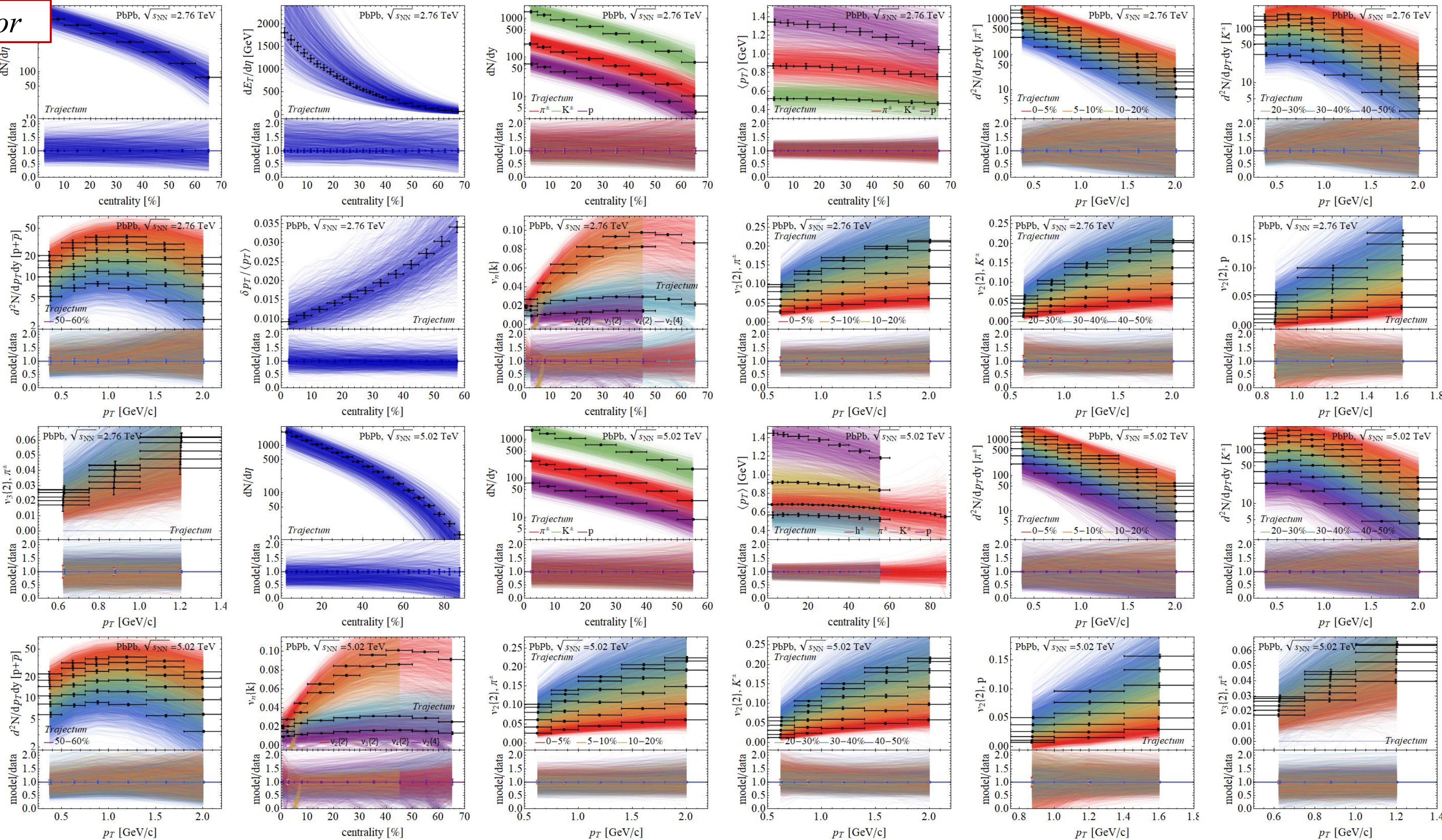
- Can include high statistics run

Same technique: gravitational waves

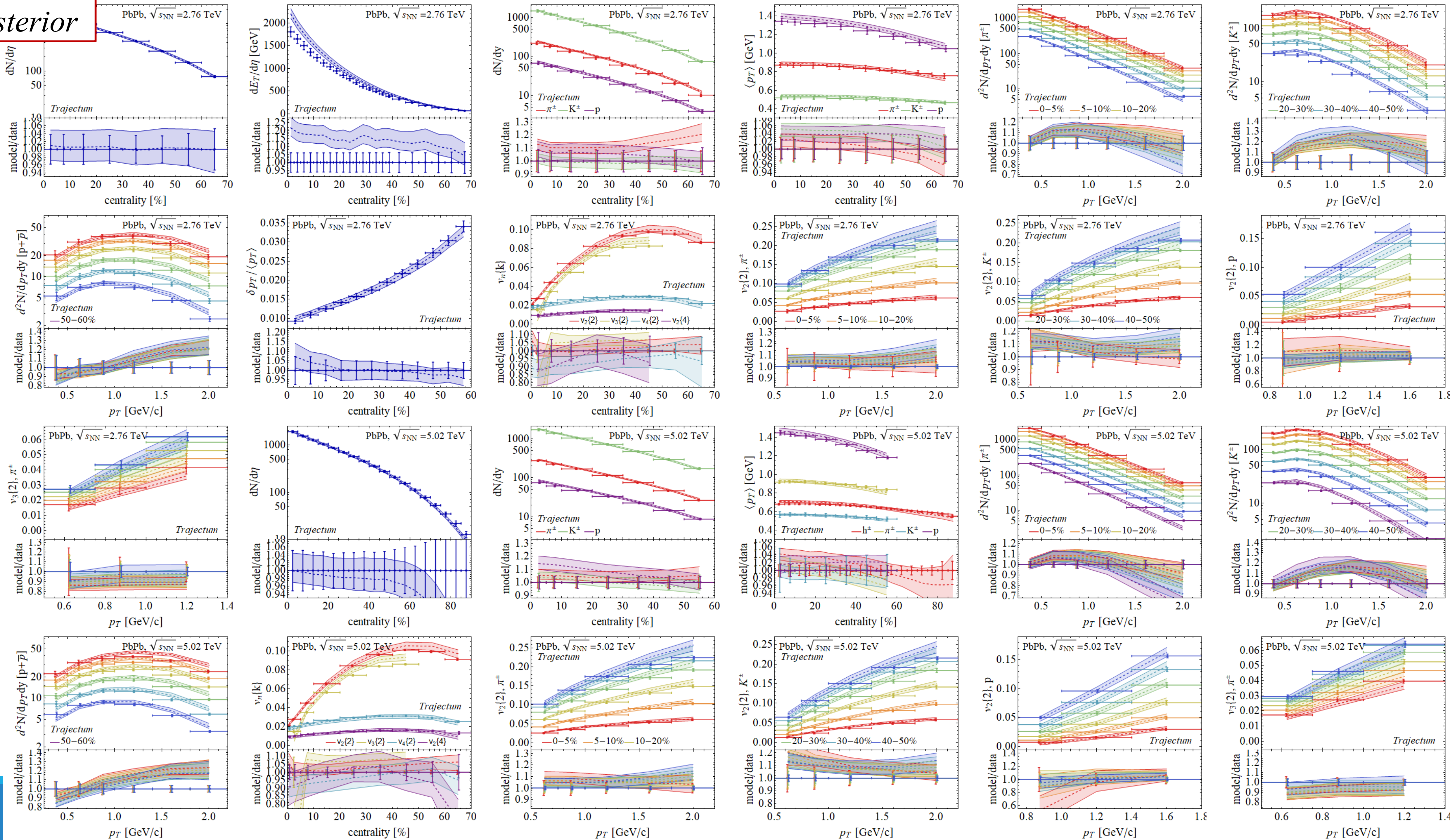




Prior


PbPb, $\sqrt{s_{NN}}$ =2.76 TeV
PbPb, $\sqrt{s_{NN}}$ =5.02 TeV
Trajectum
dN/dη
dE_T/dη [GeV]
dN/dy
⟨p_T⟩ [GeV]
$d^2N/dp_T dy$ [$\pi^\pm$]
$d^2N/dp_T dy$ [$K^\pm$]
$d^2N/dp_T dy$ [$p+\bar{p}$]
$\delta p_T / \langle p_T \rangle$
$v_n\{k\}$
$v_2\{2\}, \pi^\pm$
$v_2\{2\}, K^\pm$
$v_2\{2\}$, p
$v_3\{2\}, \pi^\pm$
model/data
centrality [%]
p_T [GeV/c]
$\pi^\pm$ — $K^\pm$ — p
$h^\pm$ — $\pi^\pm$ — $K^\pm$ — p
0–5% 5–10% 10–20%
20–30% 30–40% 40–50%
50–60%
$v_2\{2\}$ $v_3\{2\}$ $v_4\{2\}$ $v_2\{4\}$

Posterior

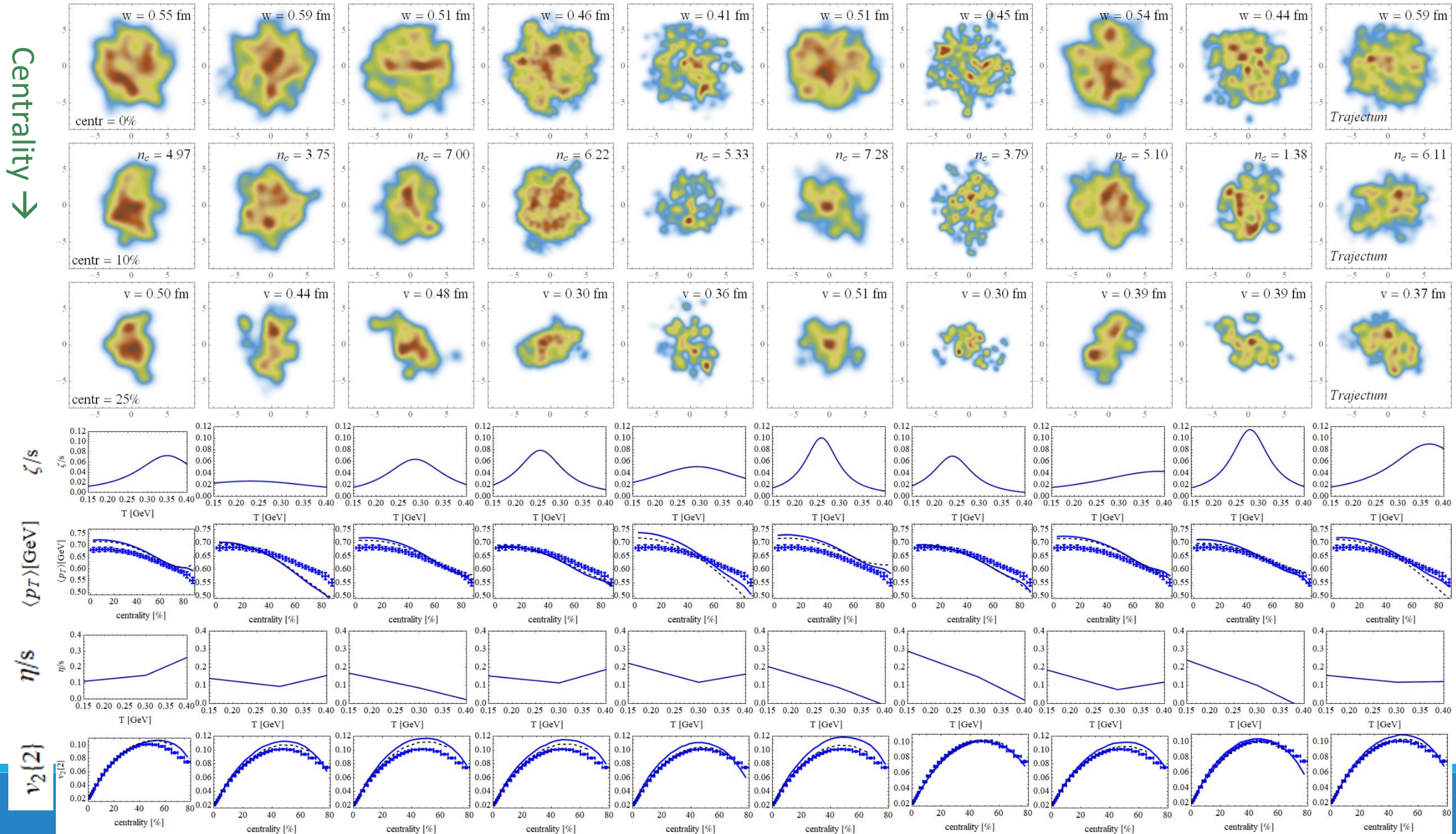


PbPb, $\sqrt{s_{NN}}$ =2.76 TeV
PbPb, $\sqrt{s_{NN}}$ =5.02 TeV
Trajectum
dN/dη
$dE_T/d\eta$ [GeV]
dN/dy
$\langle p_T \rangle$ [GeV]
d^2N/dp_Tdy [$\pi^\pm$]
d^2N/dp_Tdy [$K^\pm$]
d^2N/dp_Tdy [$p+\bar{p}$]
$\delta p_T / \langle p_T \rangle$
$v_n\{k\}$
$v_2\{2\}, \pi^\pm$
$v_2\{2\}, K^\pm$
$v_2\{2\}$, p
$v_3\{2\}, \pi^\pm$
model/data
centrality [%]
p_T [GeV/c]
$\pi^\pm$ — $K^\pm$ — p
$h^\pm$ — $\pi^\pm$ — $K^\pm$ — p
0–5% — 5–10% — 10–20%
20–30% — 30–40% — 40–50%
50–60%
$v_2\{2\}$ — $v_3\{2\}$ — $v_4\{2\}$ — $v_2\{4\}$

Energy + viscosities + experiment

Ten different probable parameter settings →

Centrality →

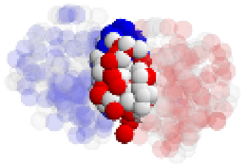


The nucleon width and the total PbPb hadronic cross section

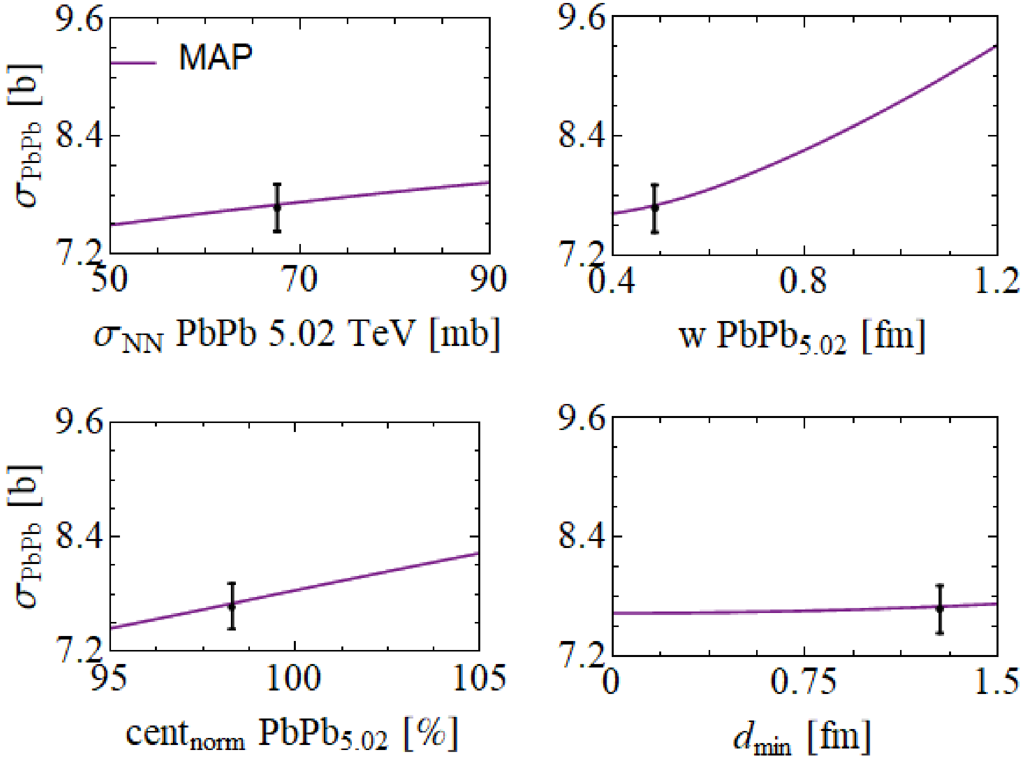
What is easier to measure the width than by simply measuring the size?

Fix nucleon-nucleon cross section:

$$P_{\text{coll}} = 1 - \exp\left[-\sigma_{gg} \int dx\, dy \int dz\, \rho_A \int dz\, \rho_B\right]$$



e.g. collision probability tuned to σ_{NN} for Gaussian profile ρ



Theoretically, cross section only depends on

- Nucleon-nucleon cross section
- Nucleon Gaussian width (dominant)
- Centrality normalisation
- Minimum inter-nucleon spacing

Makes the cross section a robust observable

- Basically implying every model needs to get this right
- Basically implying the nucleon width should be small

Why was the width overestimated?

	$\sigma_{\mathrm{PbPb}}[b]$	$\sigma_{p\mathrm{Pb}}[b]$
σ_{AA} & weights	8.03±0.19	2.20±0.06
weights	9.00±0.34	2.50±0.10
σ_{AA}	8.13±0.19	2.23±0.06
neither	8.72±0.29	2.41±0.09
ALICE	7.67±0.24	2.06±0.08

Without cross section width is large, about 1.0 fm

With the cross section width is smaller, about 0.7 fm

- Still tension with cross section: other data pushes width higher

Need to capture `trust' in observables: **weighting**

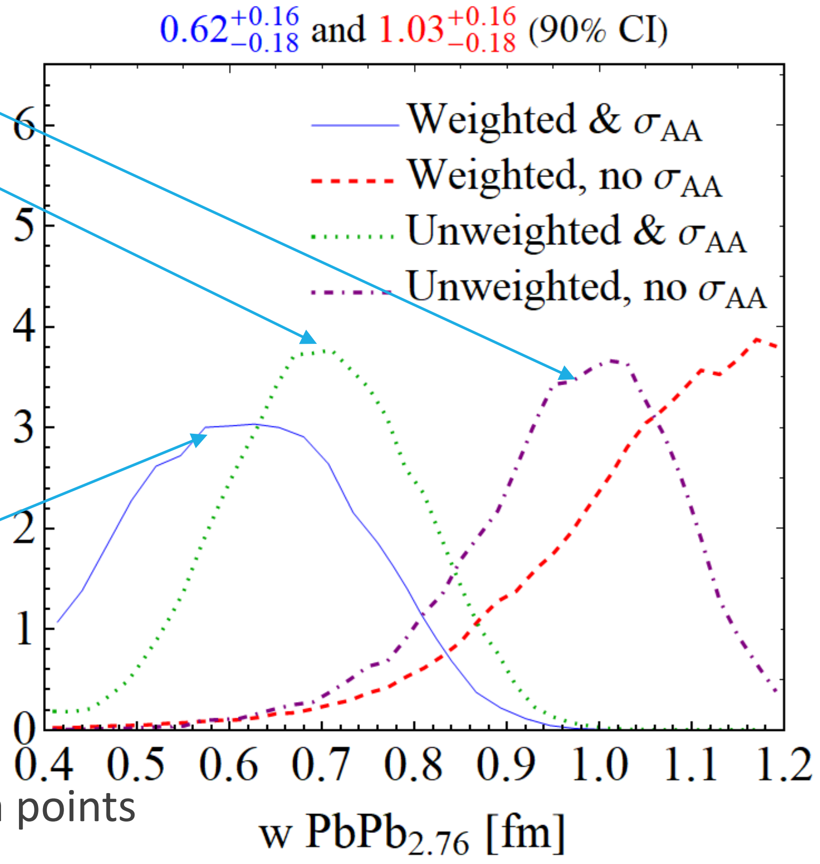
- Weight unity: cross section + integrated & unidentified
- Weight ½: integrated identified observables
- Weight ¼: p_T-differential identified observables
- Reduced weight: p_T > 1.5 GeV (π+K) and centrality > 50%

With weighting cross section comes out correctly

- Broader uncertainties: reflect less `trust' due to weighting

Also: description of data not much worse with smaller width

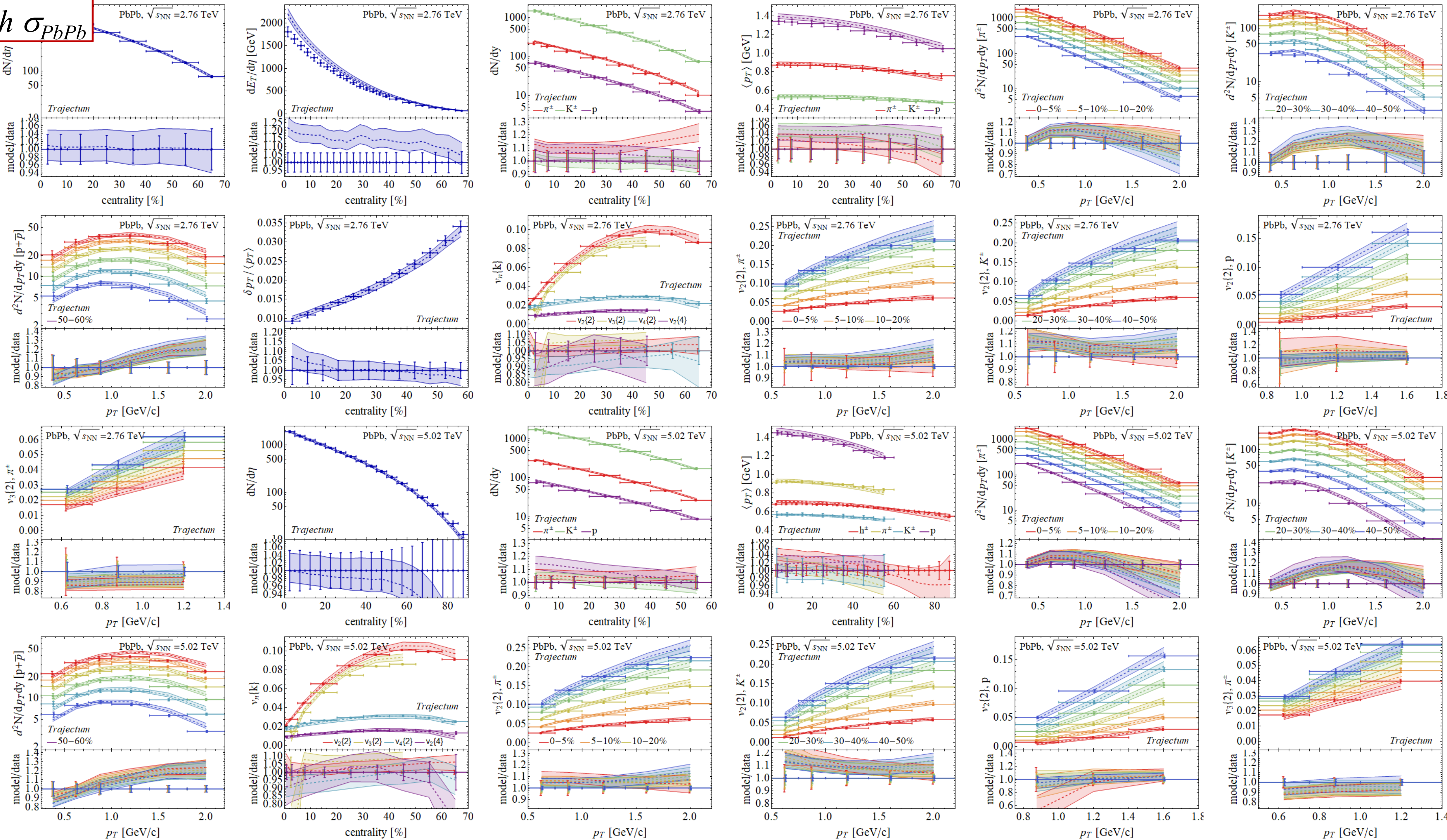
- Important that Bayes factor is an addition of many (correlated!) data points



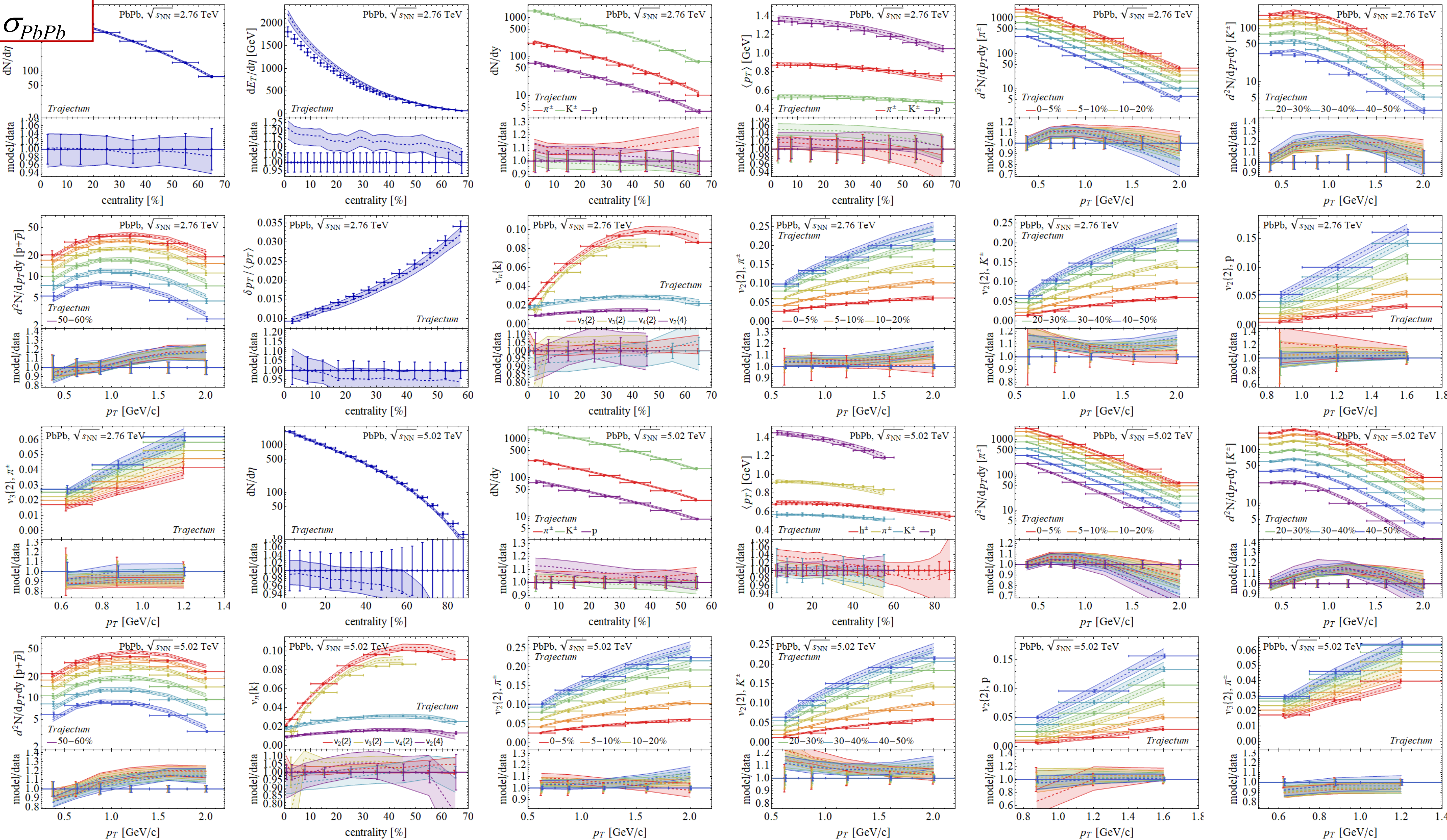
$$\mathcal{P}(\boldsymbol{x}|\mathbf{y}_{\mathrm{exp}}) = \frac{e^{-\Delta^2/2}}{\sqrt{(2\pi)^n \det(\Sigma(\boldsymbol{x}))}}\mathcal{P}(\boldsymbol{x})$$

with $\Delta^2 = (\mathbf{y}(\boldsymbol{x}) - \mathbf{y}_{\mathrm{exp}}) \cdot \Sigma(\boldsymbol{x})^{-1} \cdot (\mathbf{y}(\boldsymbol{x}) - \mathbf{y}_{\mathrm{exp}})$

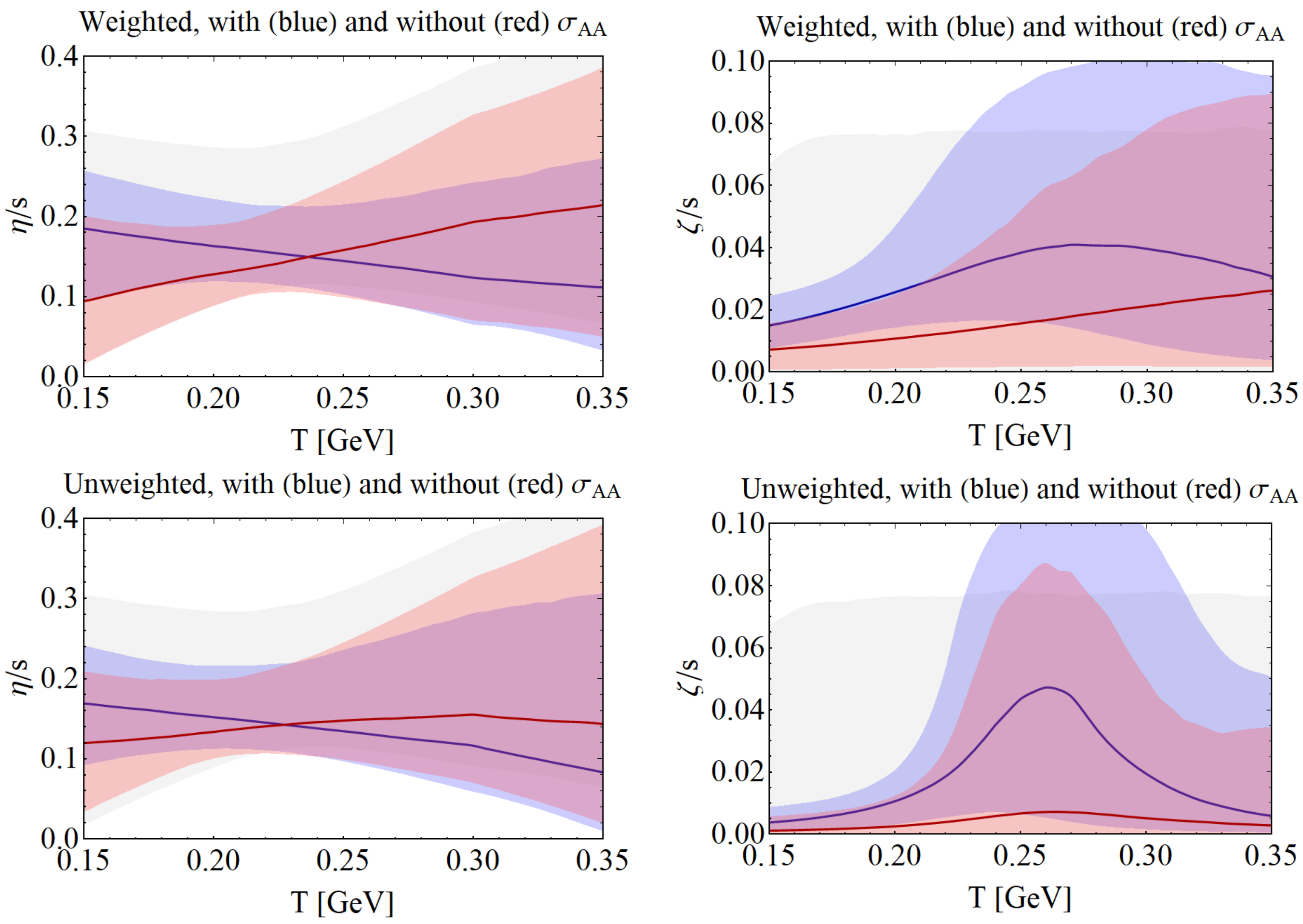
With σ_{PbPb}



No σ_{PbPb}



Effect on the viscosities



Smaller width:

- Increased bulk viscosity to counter radial flow
- Hint of increase in η/s at low temperature

Weighting data:

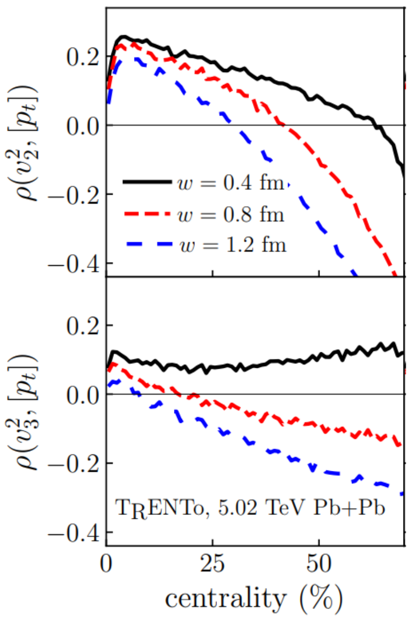
- Increases size bulk viscosity (consistent with width)
- Larger uncertainty bulk, especially at low T
- Shear viscosity almost unperturbed

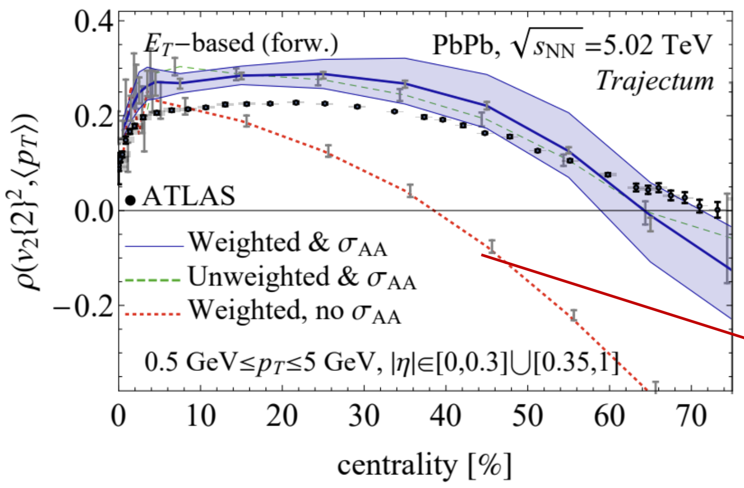
Bonus: mean p_T and v_2 or v_3 correlations

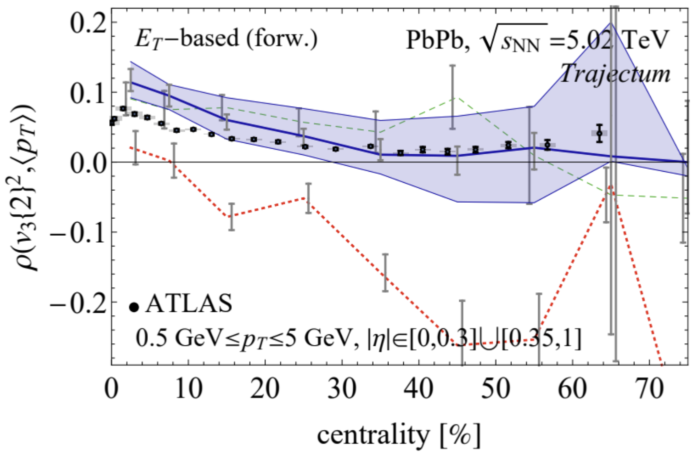
A Bayesian MAP check: unfitted data:

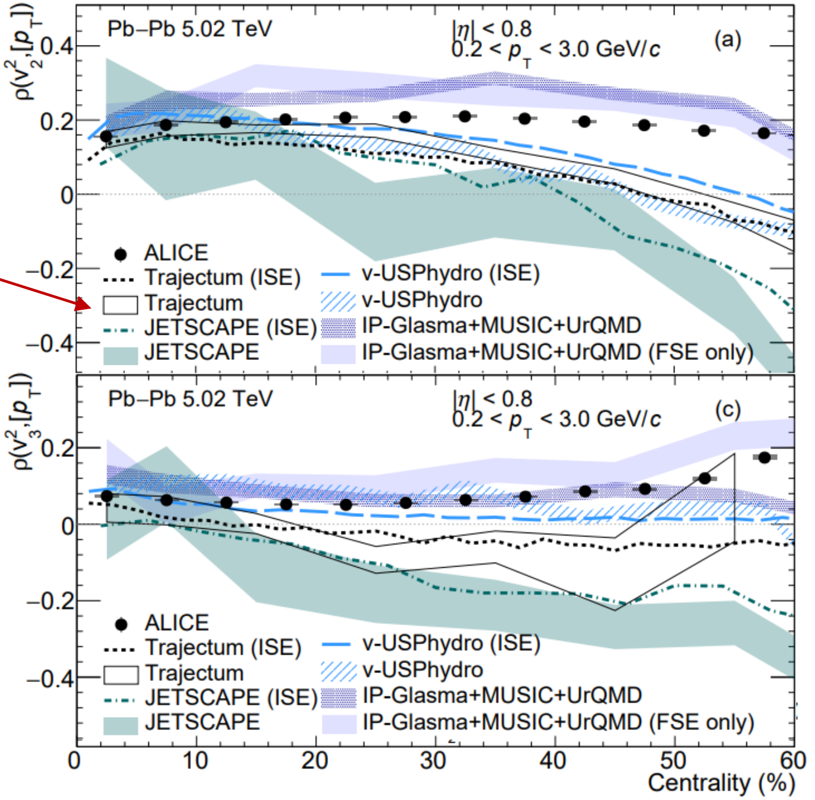
- Triple differential observables:
- Correlation p_T and v_n

Anticipated by (simpler) Trento analysis:









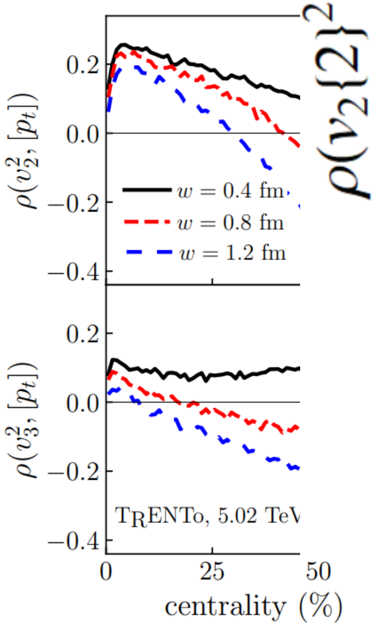
Bonus: mean p_T and v_2 or v_3 correlations

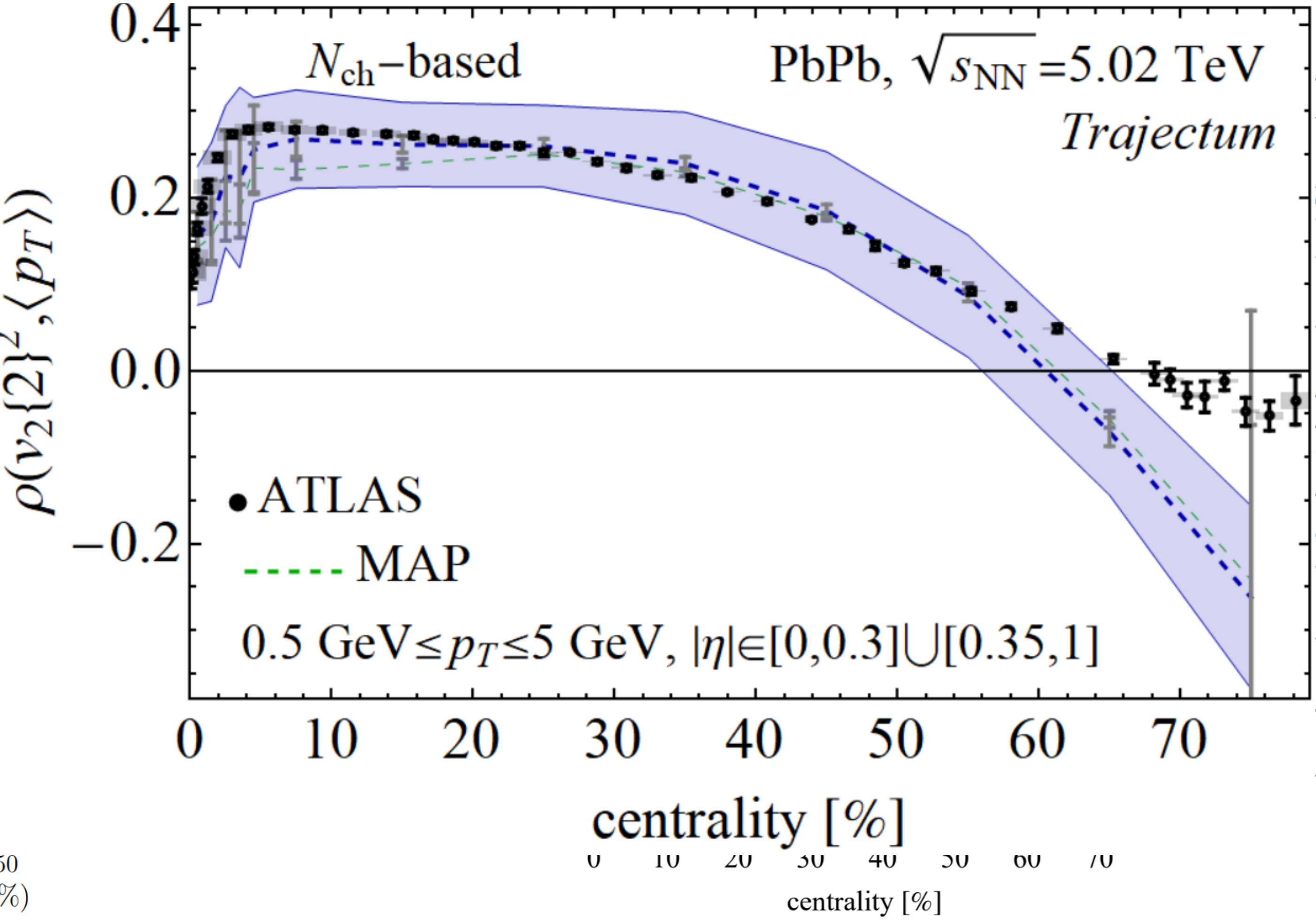
NEW AT INT

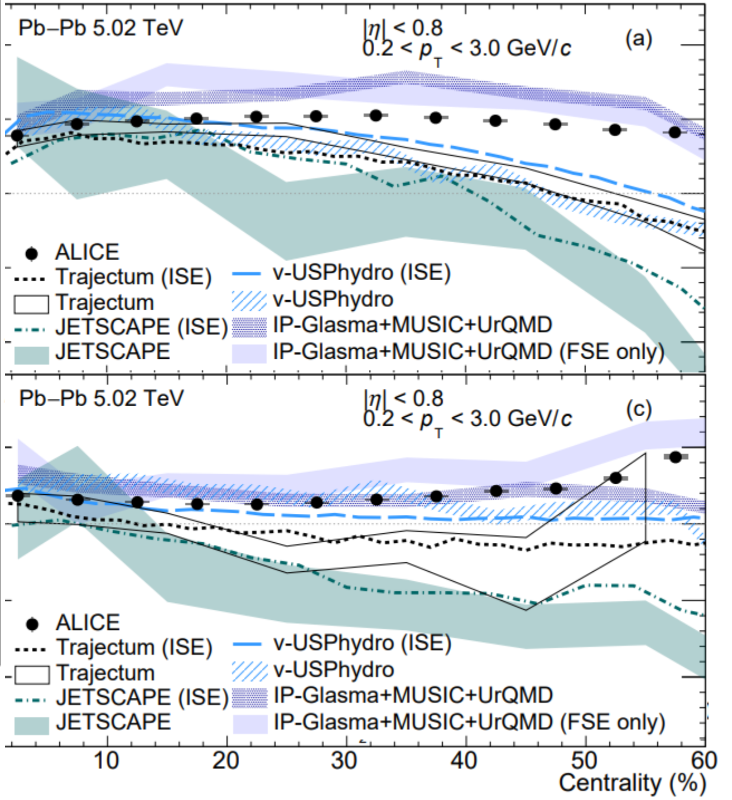
A Bayesian MAP check: unfitted data:

- Triple differ
- Correlation

Anticipated b
Trento analys

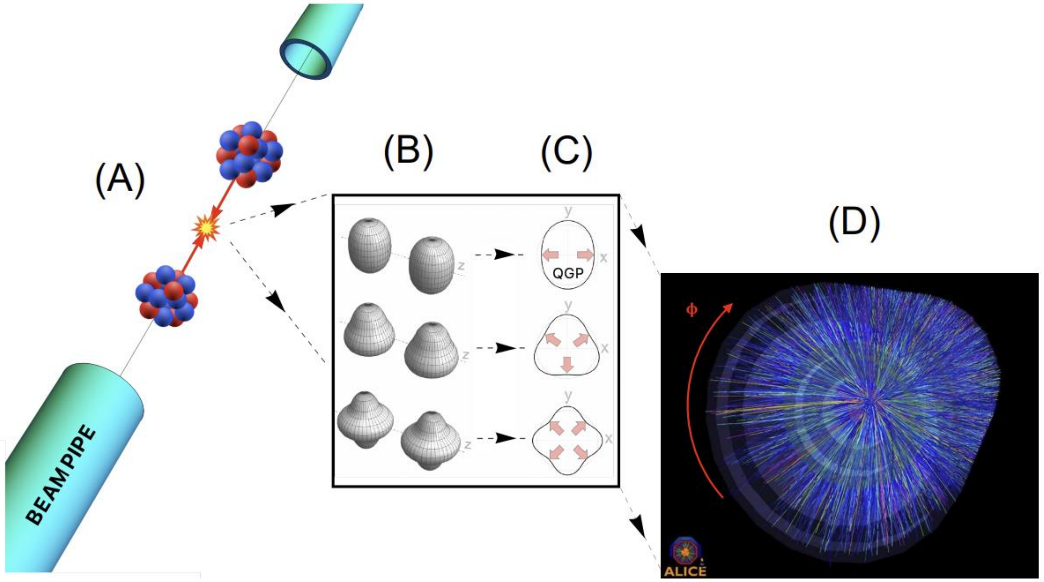




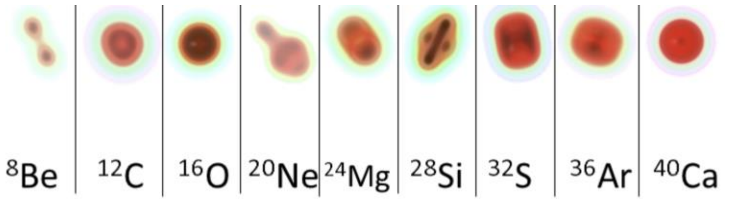


Giuliano Giacalone, Bjorn Schenke and Chun Shen, Constraining the nucleon size with relativistic nuclear collisions (2021)
ALICE, Characterizing the initial conditions of heavy-ion collisions at the LHC with mean transverse momentum and anisotropic flow correlations (2021)

The shape of nuclei



Benjamin Bally, James Daniel Brandenburg, Giuliano Giacalone, Ulrich Heinz, Shengli Huang, Jiangoyng Jia, Dean Lee, Yen-Jie Lee, Wei Li, Constantin Loizides, Matthew Luzum, Govert Nijs, Jacquelyn Noronha-Hostler, Mateusz Ploskon, WS, Bjoern Schenke, Chun Shen, Vittorio Somà, Anthony Timmins, Zhangbu Xu and You Zhou
Imaging the initial condition of heavy-ion collisions and nuclear structure across the nuclide chart (2022)



Nuclear structure and heavy ion collisions

Isobar collisions raise several questions:

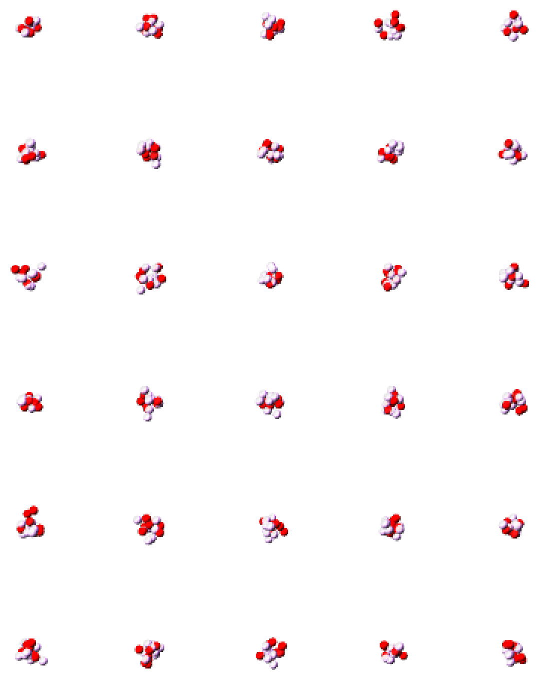
- Are HIC sensitive to nuclear structure? Yes, but at percent level accuracy
- Are HIC understood at percent level? Historically likely not…

A more systematic approach

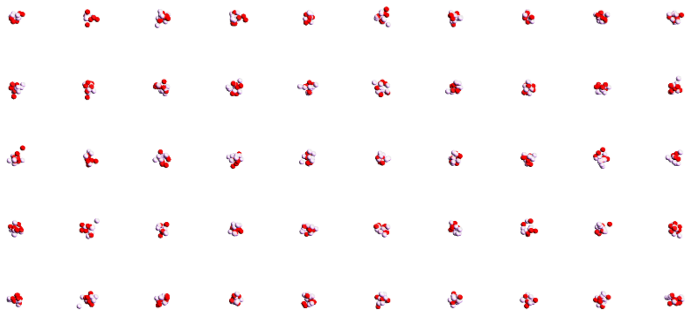
- Vary several approaches to nuclear structure
- Vary parameter settings within current posterior distribution
- Do we need an (isobar) ratio to make progress?

Oxygen (and Neon?) at CERN

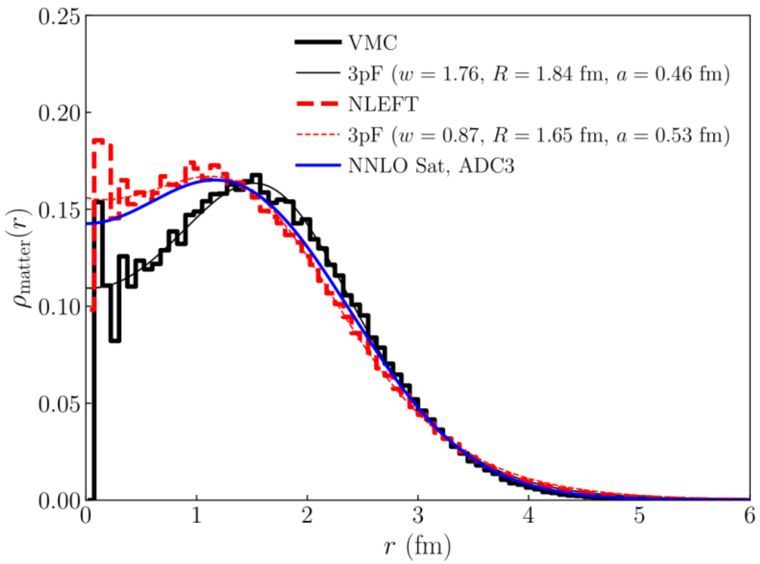
- Independently interesting: the smallest droplet of QGP, cosmic rays (p-O collisions)
- Oxygen (Neon) specifically interesting: can we see 4 (5) clusters of alpha-particles?
- Neon – Lead beam gas collisions foreseen at LHCb fixed target mode

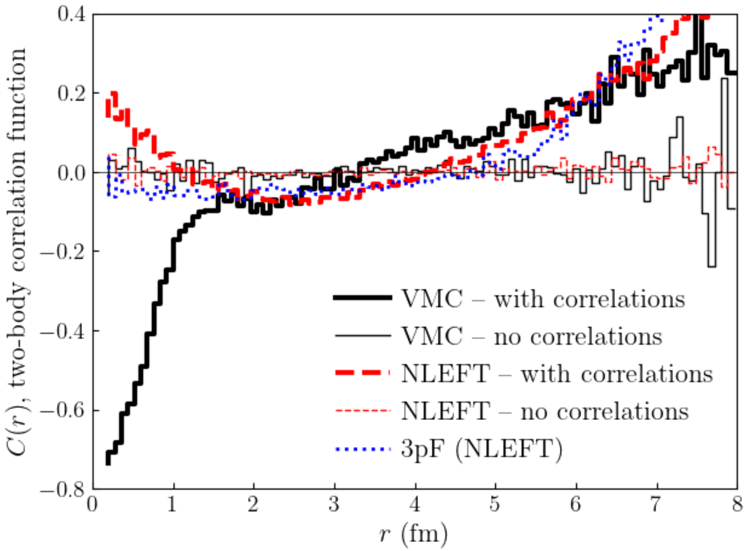


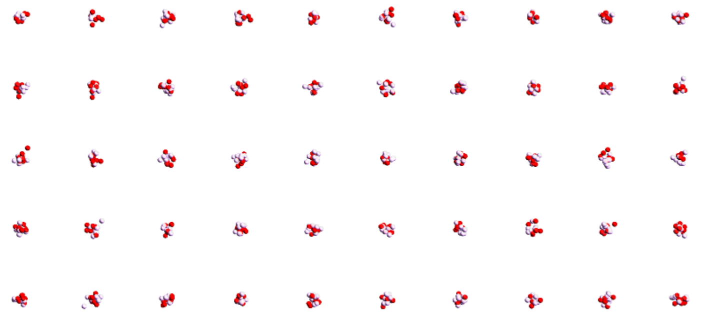
Oxygen nuclear structure



1. Comparing two state-of-the-art microscopics with old profile (MAP run with 1M hydro events per run)
   - 3pF: 3 parameter Wood-Saxon Fermi fit from 1976 with d_{min}
   - VMC: Variational Monte Carlo to sample wave function with advanced nucleon interaction, significantly disagreement with experiment for charge density.
   - NLEFT: Nuclear Lattice Effective Field Theory, ground state with `pin holes‘, no repulsive interaction implemented (?)







Oxygen nuclear structure

1. Comparing two state-of-the-art microscopics with old profile (MAP run with 1M hydro events per run)
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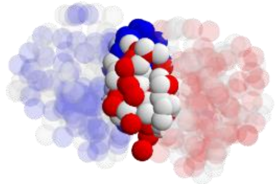
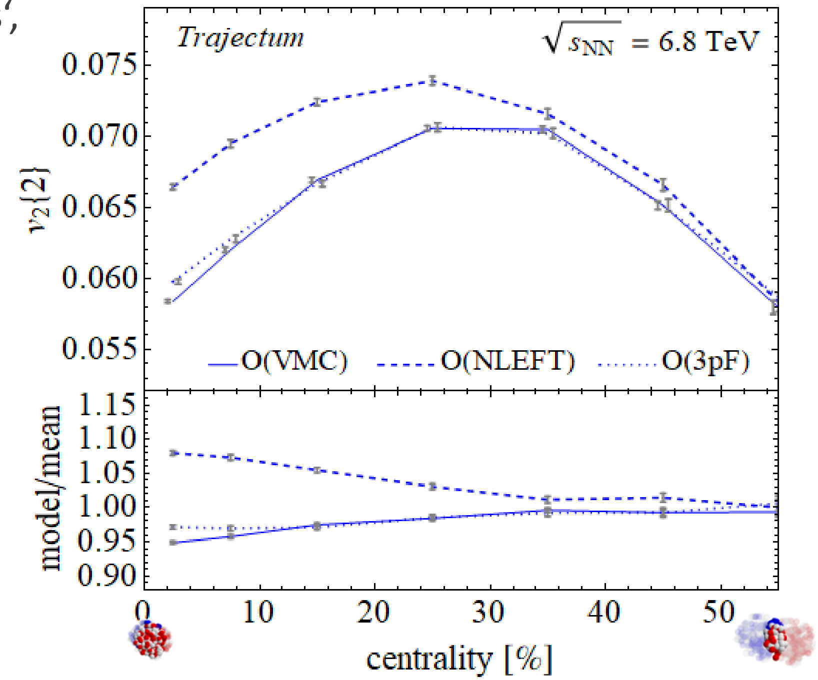


MAP settings



2. Elliptic flow does not distinguish VMC/3pF
   - Other observables can (e.g. mean transverse momentum)

3. Significant differences for central collisions

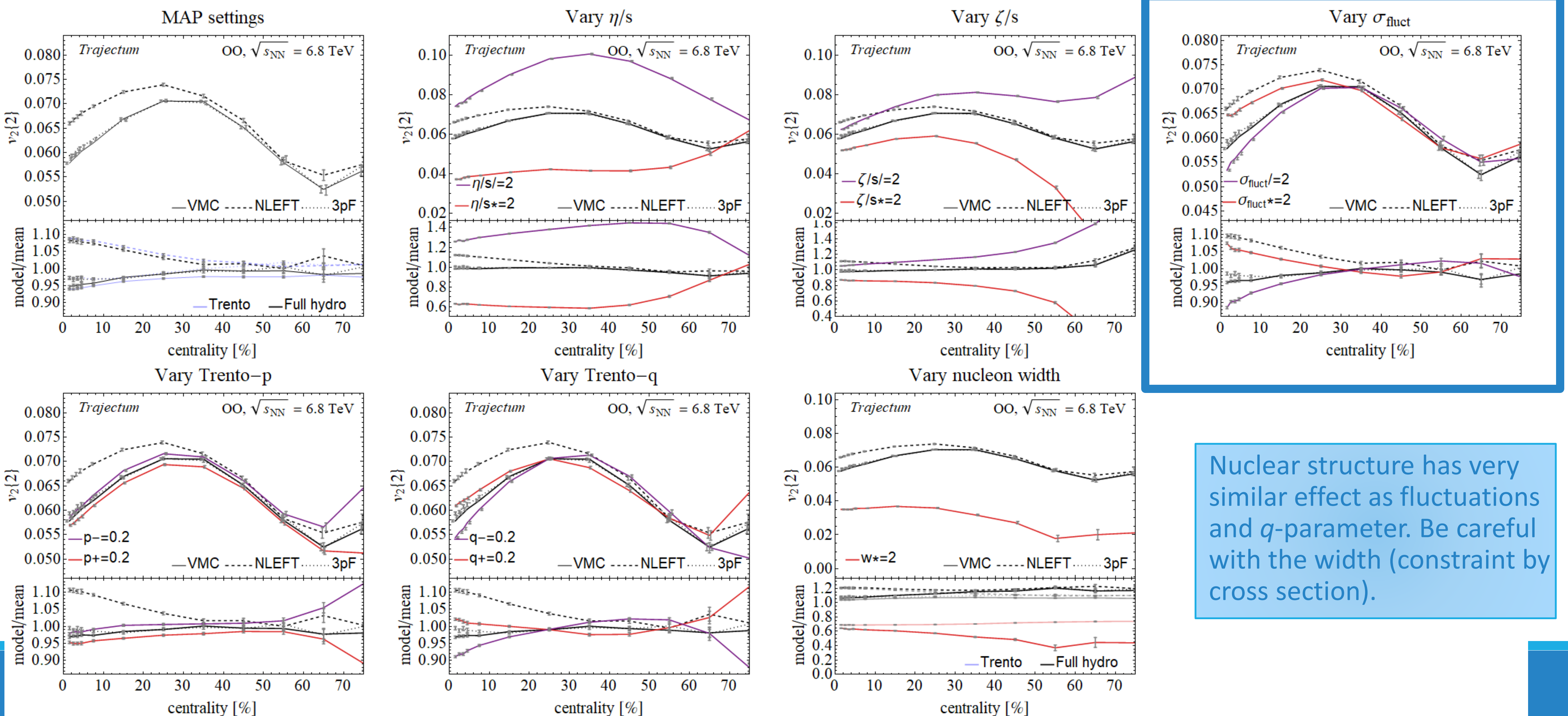
Giuliano Giacalone, Govert Nijs and WS, to appear
D. Lonardoni, A. Lovato, Steven C. Pieper and R.B. Wiringa, Variational calculation of the ground state of closed-shell nuclei up to A=40 (2017)

Elliptic flow

Vary some model parameters (for VMC only), ~1M hydro and ~100M SMASH events

Are results robust when varying parameter?

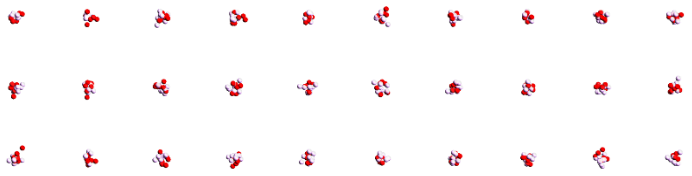
- Not really… nuclear structure similar to fluctuations

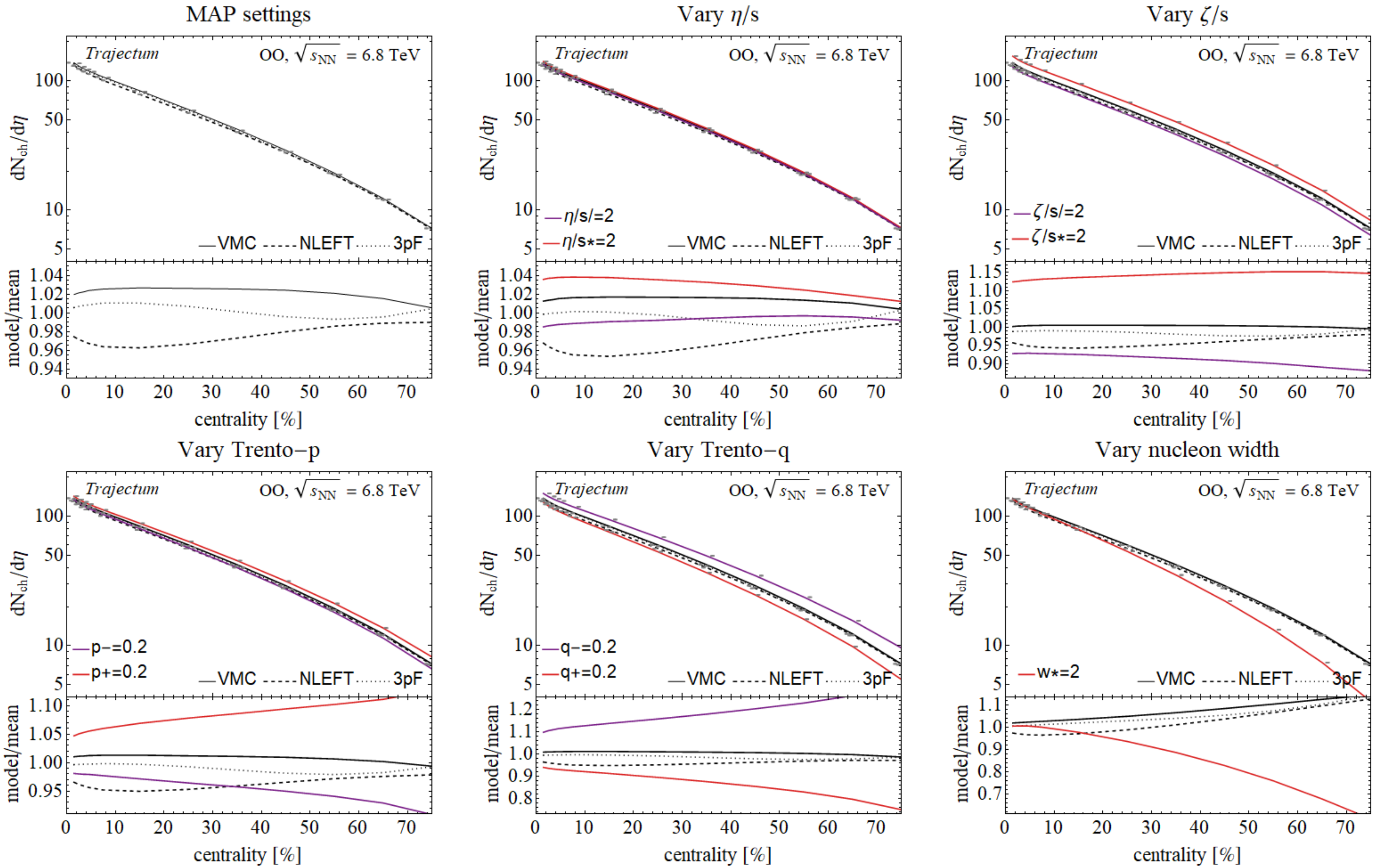


Nuclear structure has very similar effect as fluctuations and *q*-parameter. Be careful with the width (constraint by cross section).

Multiplicity

Vary some model parameters (for VMC only)

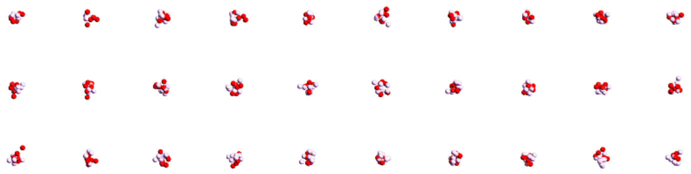


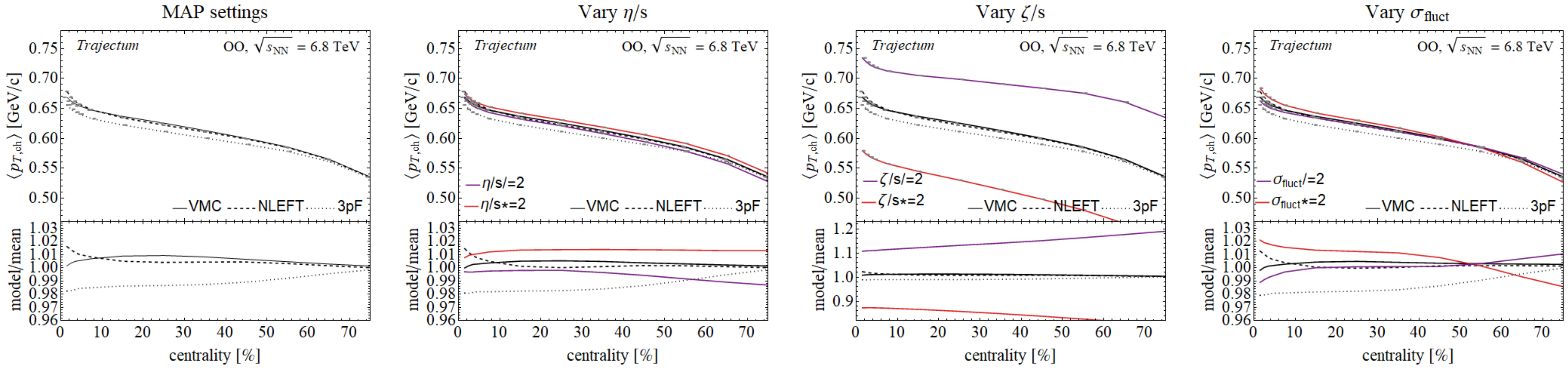


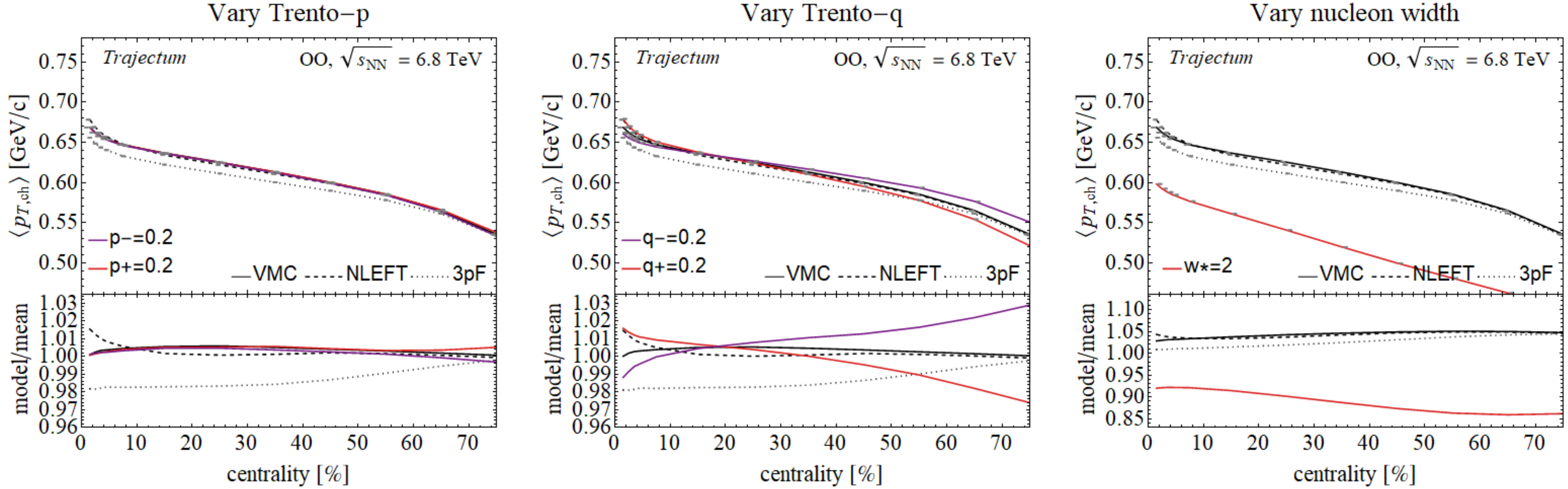
Nuclear structure has very a relatively mild effect. Not a good observable.

Mean transverse momentum

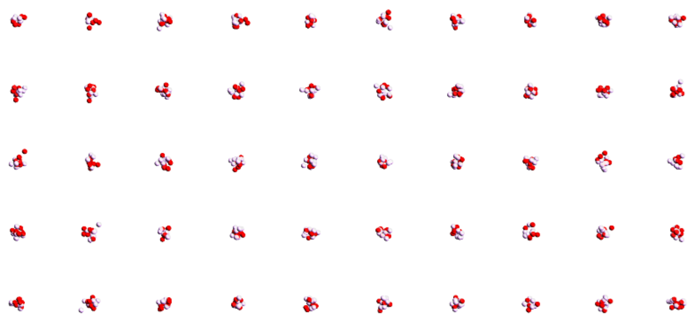
Vary some model parameters (for VMC only)





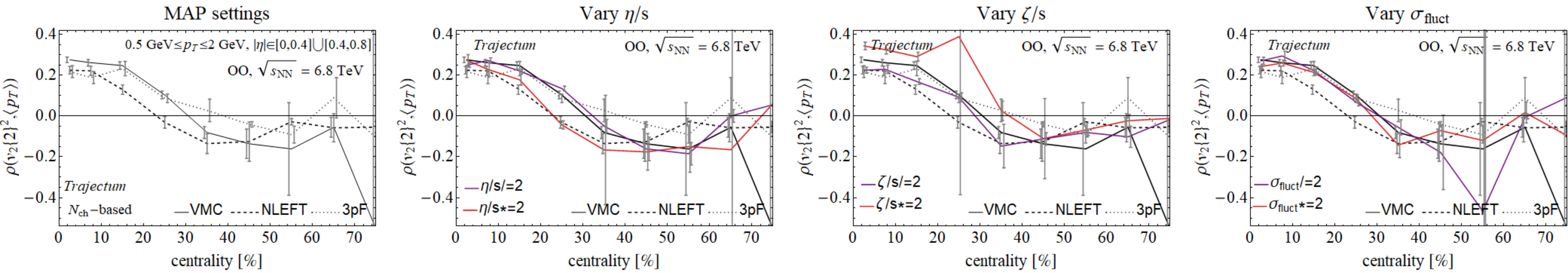


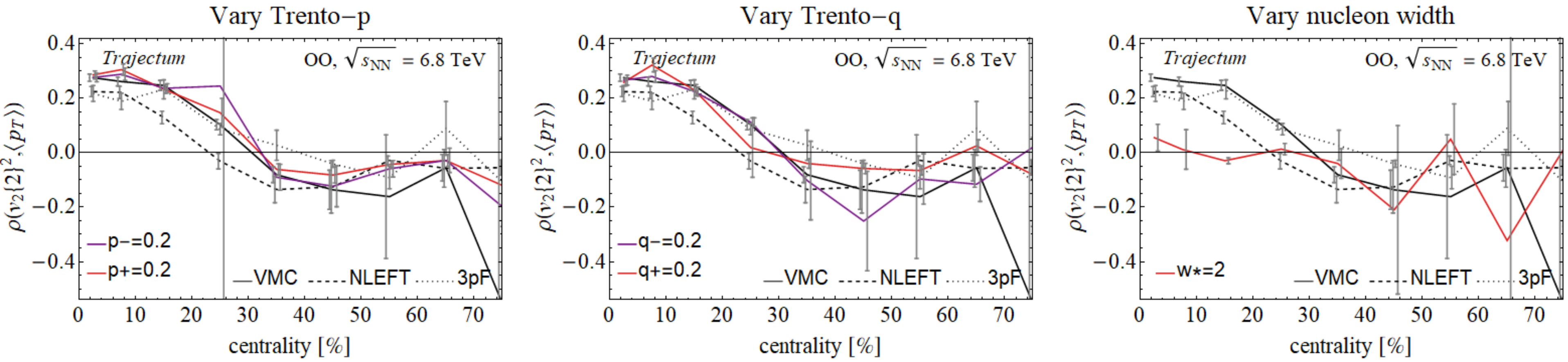
Nuclear structure has very a relatively mild effect. Not a good observable.



Correlation between v_2 and mean p_T

Vary some model parameters (for VMC only)

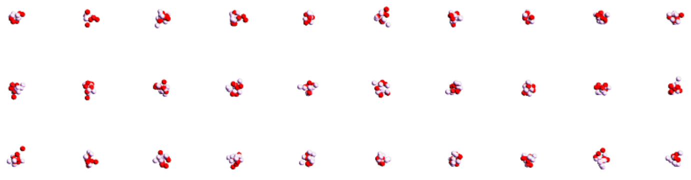


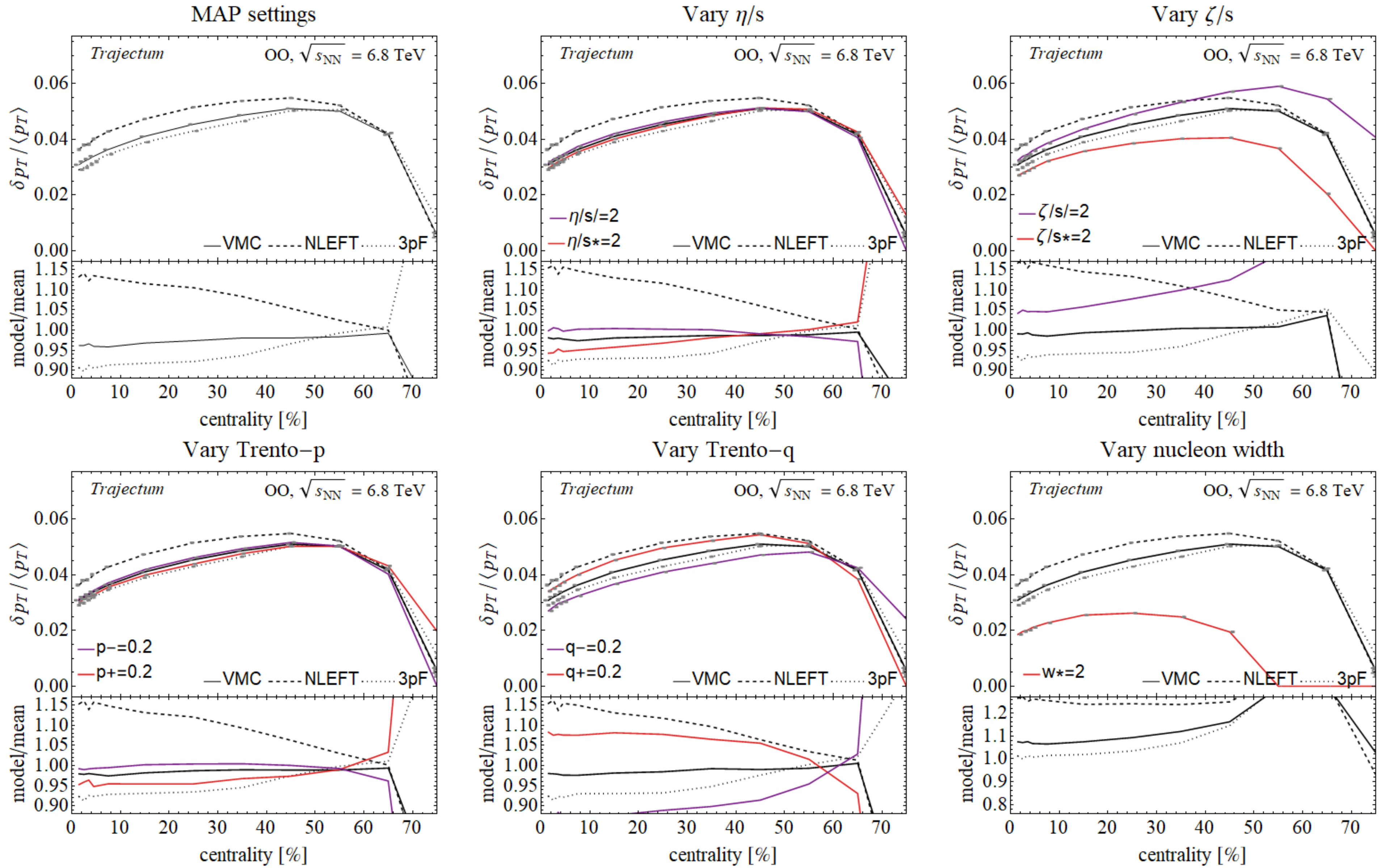


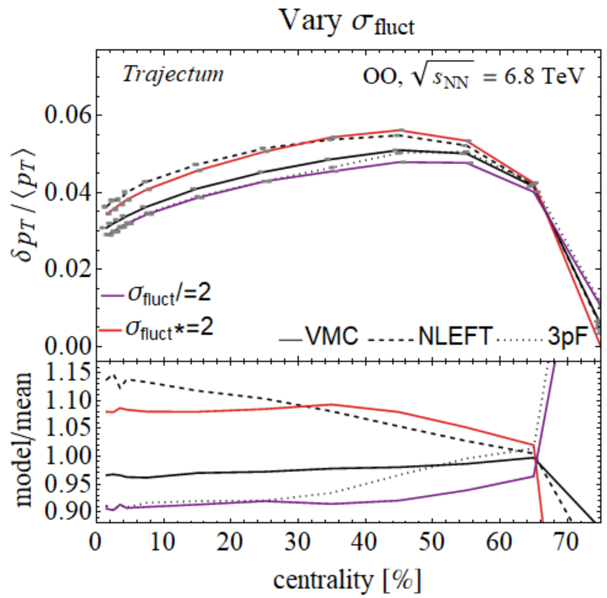
Conjectured to be a good observable. But must be careful with width and viscosities.

Transverse momentum fluctuations

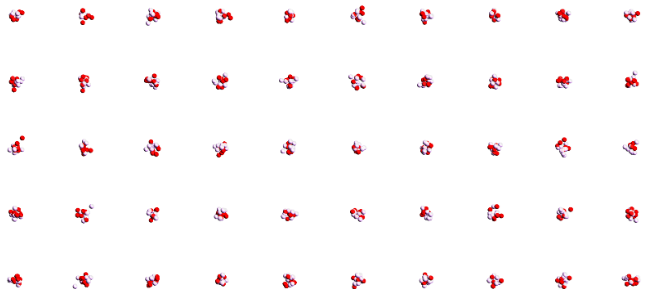
Vary some model parameters (for VMC only)







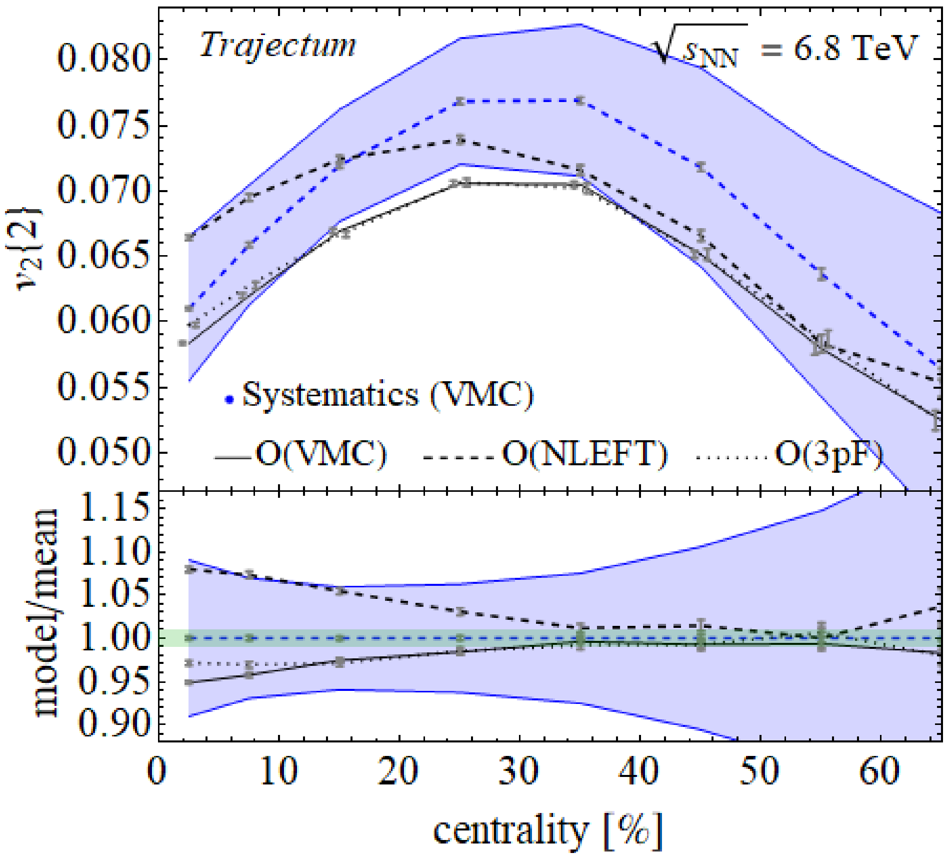
Almost indistinguishable from fluctuations in Trento. But can perhaps fix in PbPb?



Oxygen nuclear structure

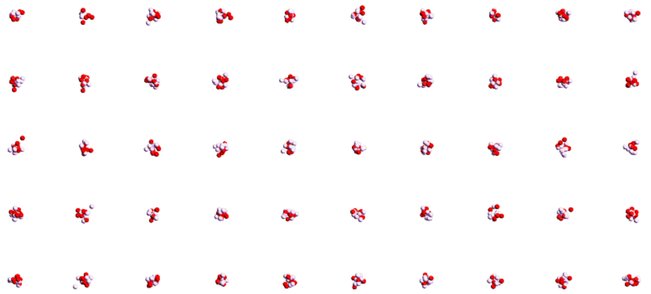
Can we do this more systematically?

- Parameters such as viscosities are highly correlated
- Take random sample of `probable' parameter settings
- Compute one standard deviation systematic uncertainty



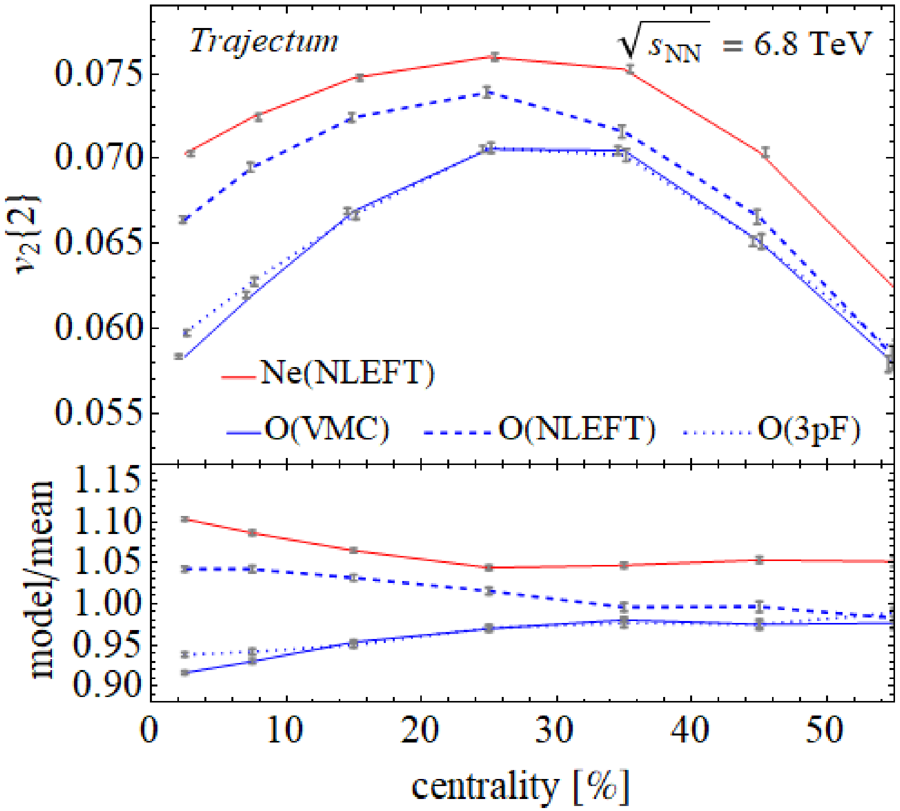
Systematic uncertainty comparable to differences due to nuclear structure

^{16}Oxygen and ^{20}Neon nuclear structure



Can we do better?

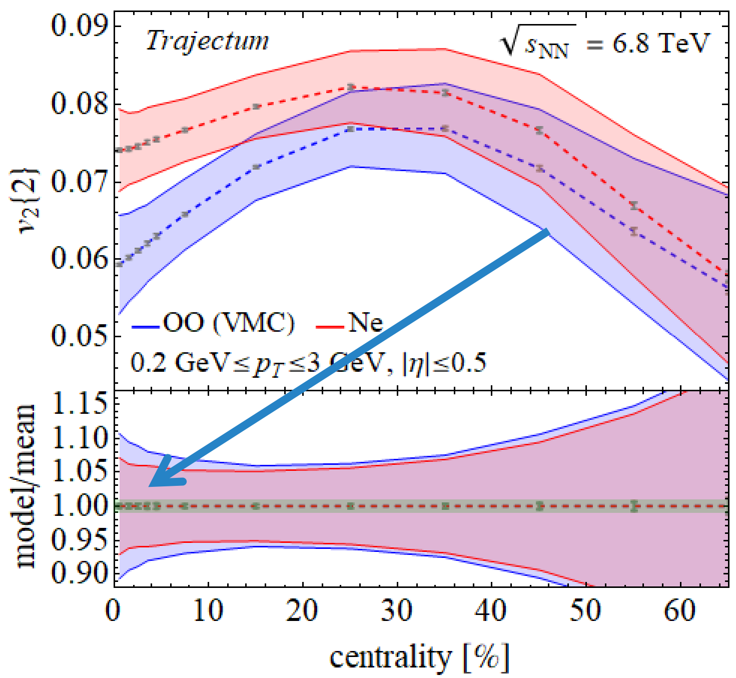
- Compare (almost) isobars: *Oxygen and Neon*
- No apples-to-apples nuclear structure available (yet)
- Neon has significantly more elliptic flow

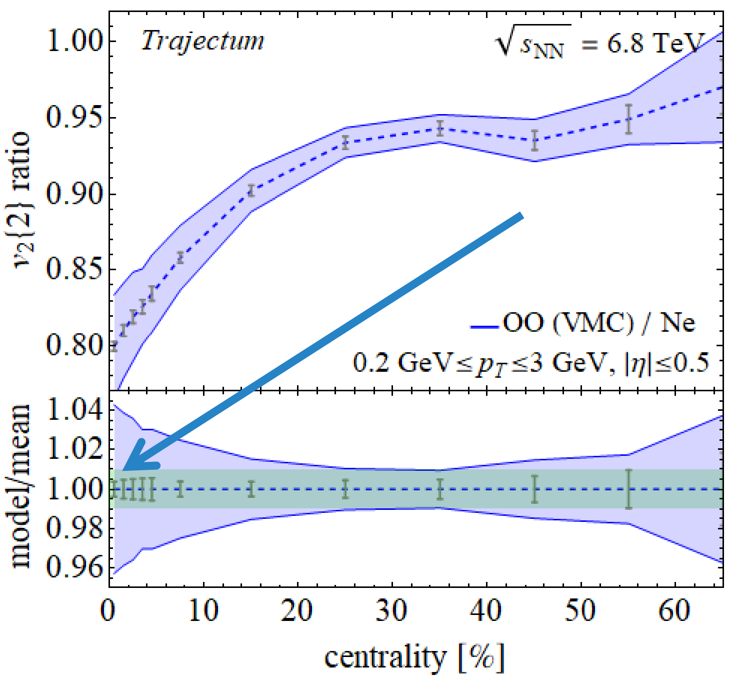


^{16}Oxygen and ^{20}Neon nuclear structure

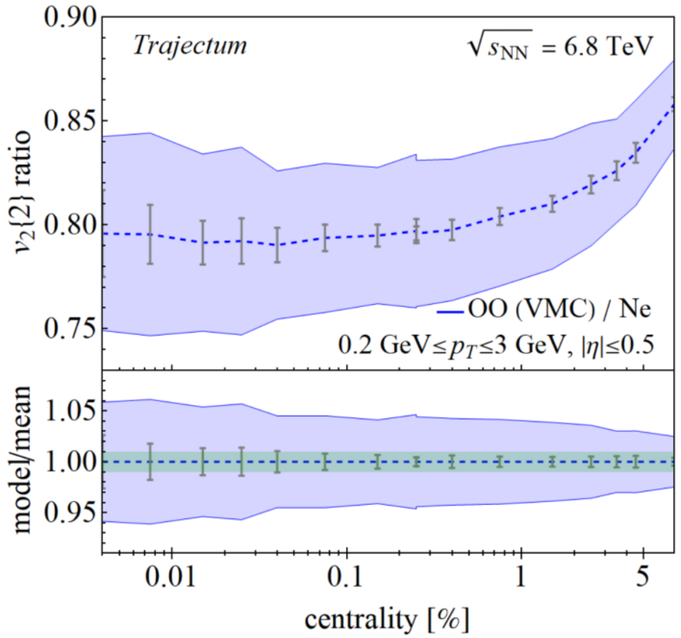
What about the systematics?

- Barely significant difference between Oxygen and Neon elliptic flow within systematics
- **The ratio**, however, is accurate at percent level (!) ***for same nuclear structure***. Sweet spot at ~25% centrality
- Could be an expensive fact …
- Curiously gets less precise around 0.01% centrality (due to OO)

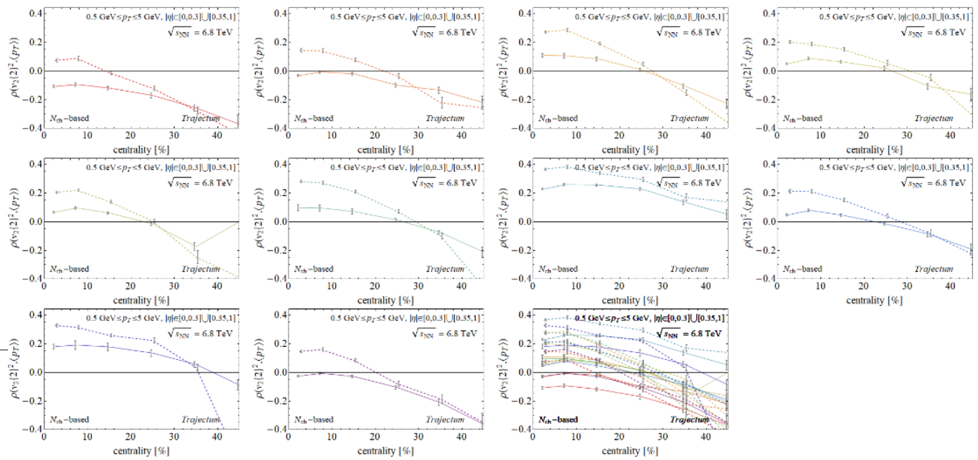




Ultracenral:

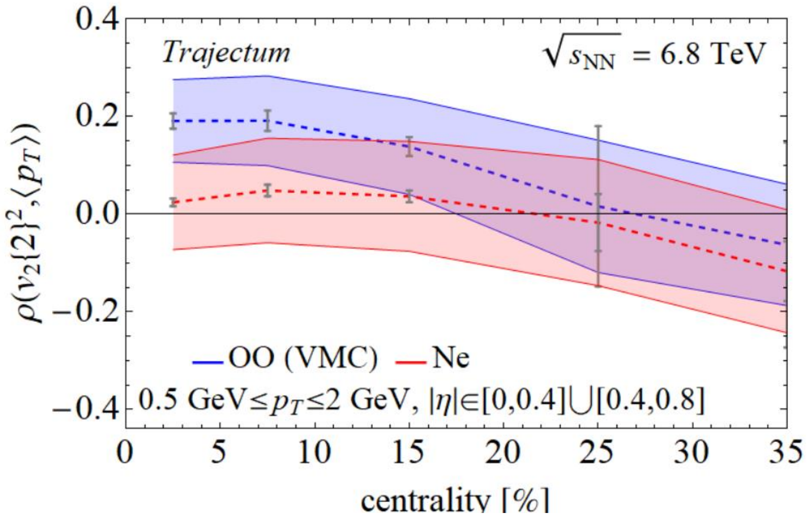


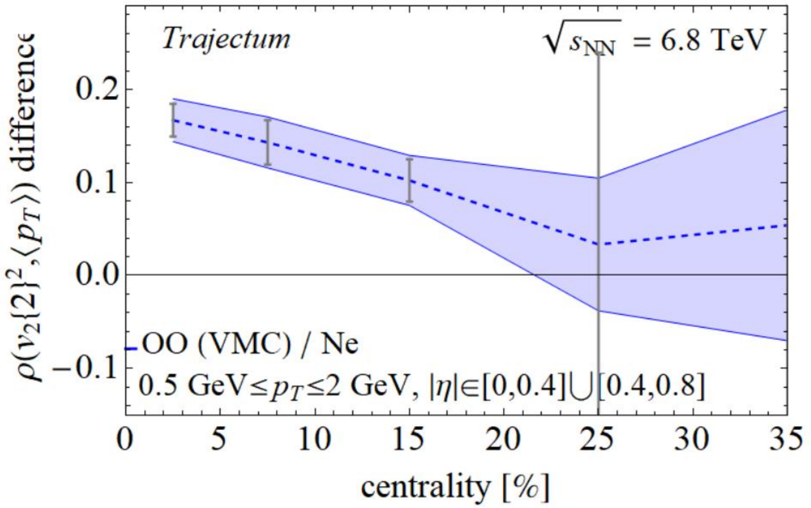
^{16}Oxygen and ^{20}Neon nuclear structure – [v_2, mean pT]-correlator:



Similarly for ρ_2 correlator

Difference is robust

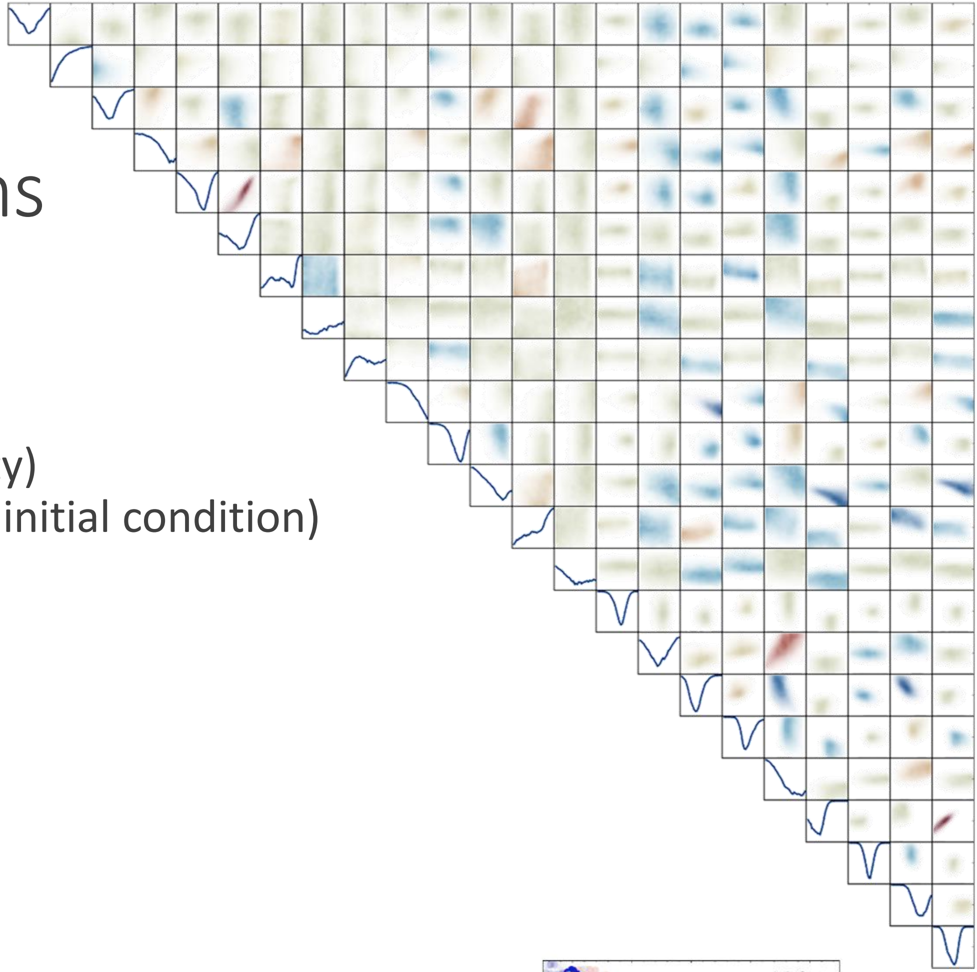




Studies raise several important questions

Previous Bayesian estimates overestimated nucleon width

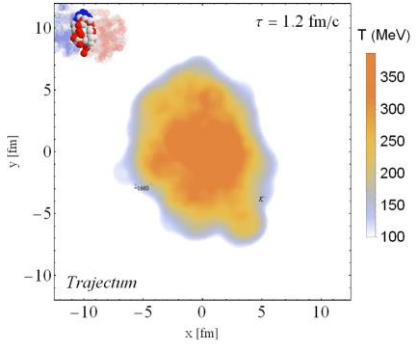
- ALICE PbPb cross section implies $w \sim 0.4 - 0.6$ fm
- difficult balance between many parameters (reducing predictivity) and artificially constraining model (like energy versus entropy in initial condition)



Exciting progress using isobars and nuclear structure

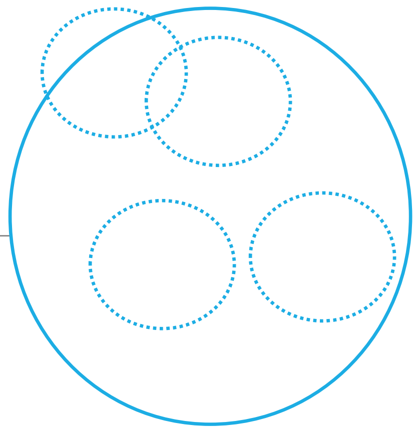
- Heavy ion collisions towards percent level precision
- Will feature also as improved understanding of QGP properties
- Oxygen collisions to be performed at the LHC summer 2024!

Neon needed for percent level science; start campaign now?



Back-up

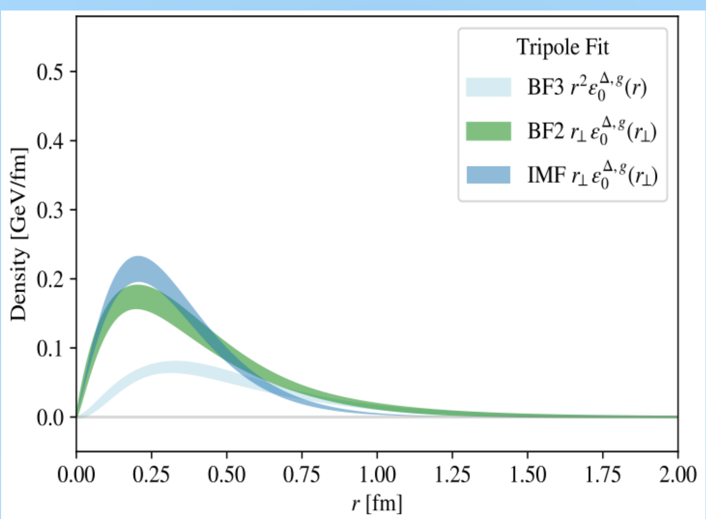
Nucleon parametrisation



The shape of nucleons

1. Nucleons are placed randomly following measured profile (Glauber)
2. Each nucleon has a Gaussian width w
   → final averaged thickness function is Gaussian
3. Each nucleon has n_c constituents:
   - Each constituent sources a Gaussian of width v
   - Each constituent fluctuates according to a gamma distribution
4. NB: QGP physics by gluons
   no relation n_c and valence quarks
5. Four parameters: w, n_c, v, *fluct*

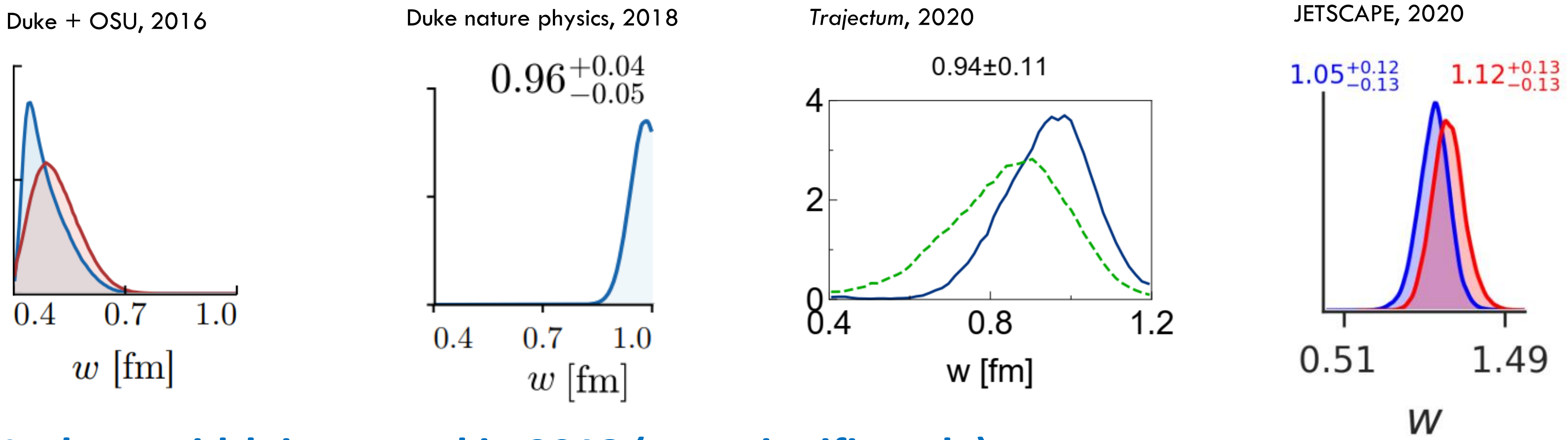
Spoiler: can we use lattice input?



Dimitra A. Pefkou, Daniel C. Hackett and Phiala E. Shanahan, Gluon gravitational structure of hadrons of different spin (2021)

The nucleon width from Bayesian scans

Nucleons grow with collision energy, but by how much?



Nucleon width increased in 2018 (very significantly)

- Includes initial stage (free streaming)
- Switched initial condition from entropy to energy
- Realistic bulk viscous corrections at particlisation

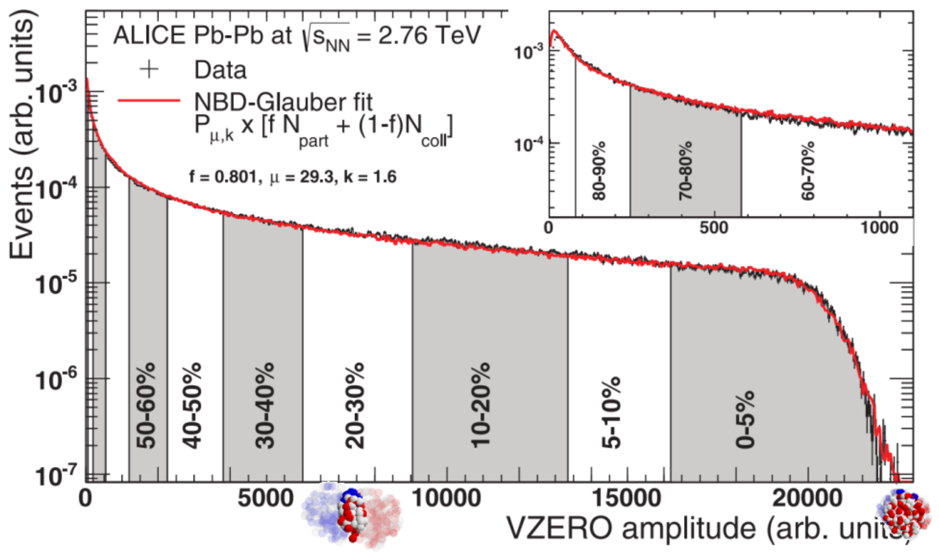
- Initial stage gives more radial flow, which is countered by larger width
- w is Gaussian width: nucleons would have ~5 fm diameter
- Such large nucleons are unlikely: cut off prior at 1 fm

PhD thesis Jonah Bernhard (p157)

Jonah Bernhard, Scott Moreland, Steffen Bass, Jia Liu and Ulrich Heinz, Applying Bayesian parameter estimation to RHIC (2016)
Jonah Bernhard, Scott Moreland and Steffen Bass, Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma (2019)
Govert Nijs, WS, Umut Gursoy and Raimond Snellings, A Bayesian analysis of Heavy Ion Collisions with Trajectum (2020)
D. Everett, W. Ke, J.-F. Paquet, G. Vujanovic et al, Multi-system Bayesian constraints on the transport coefficients of QCD matter (2020)

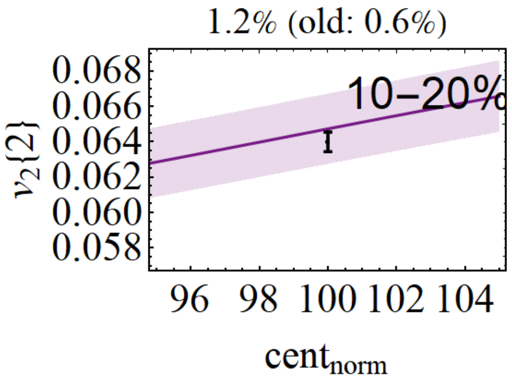
The PbPb cross section and the centrality normalisation

Cross section follows from
- Luminosity (van der Meer scan, dominates uncertainty)
- The number of collisions
- First measured in April 2022 (!)



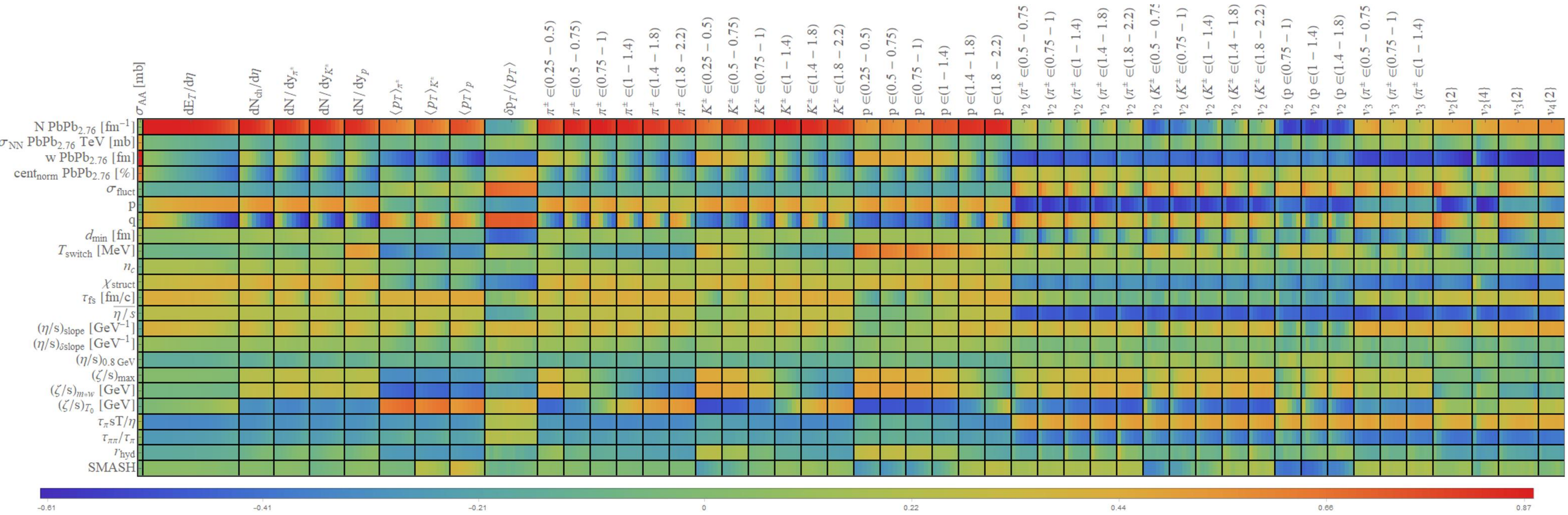
ALICE can accurately measure collisions in 0-90% region
- 90-100% is estimated from NBD Glauber fit

Trajectum defines 100% by having at least one nucleon-nucleon interaction
- Now also a parameter, perhaps as a check, or to address experimental uncertainty
- We take a Gaussian prior of width 1%



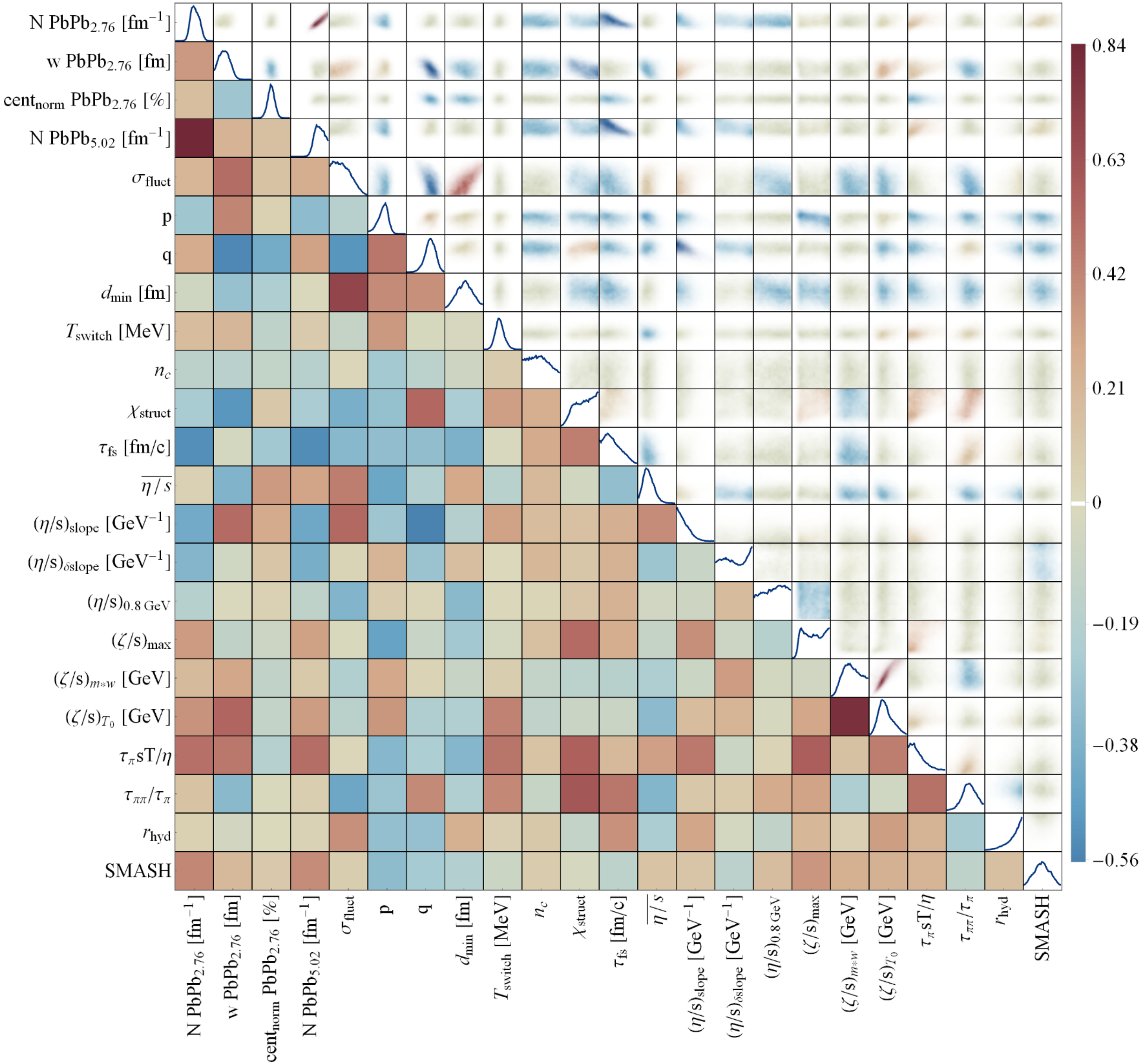
Centrality normalisation trivially correlates **all** observables by shifting classes
- Probably best to marginalise over in MCMC Bayesian analysis
- Means ALICE should quote this uncertainty separately
- Important even for some central observables ($v_2\{2\}$)

Design parameter-observable correlations:

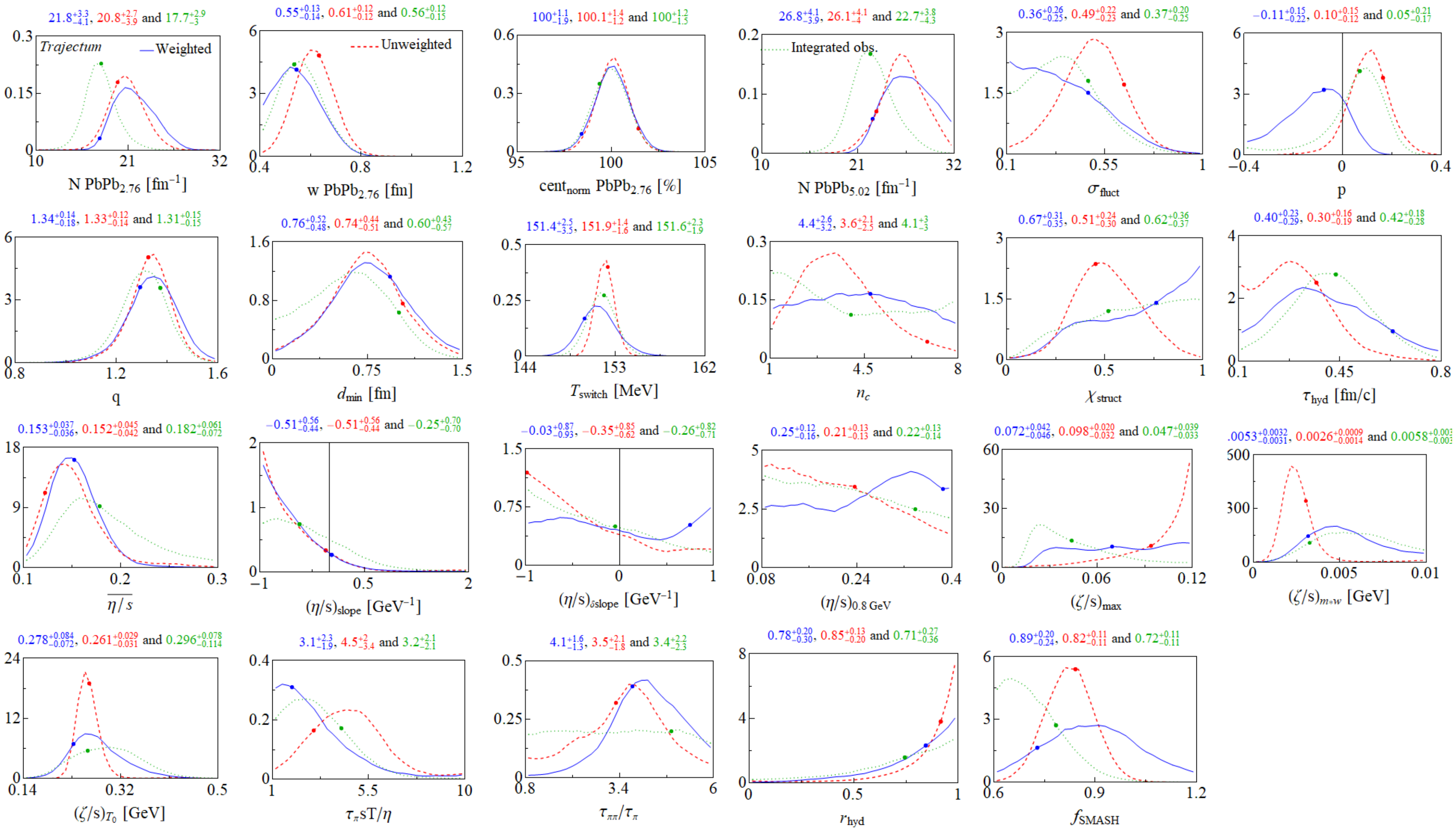


Full posterior distributions

1. Some parameters better constrained than others
   - Correlations add important information, e.g. width constrained much more accurately if *q* parameter is known



Full posterior distributions

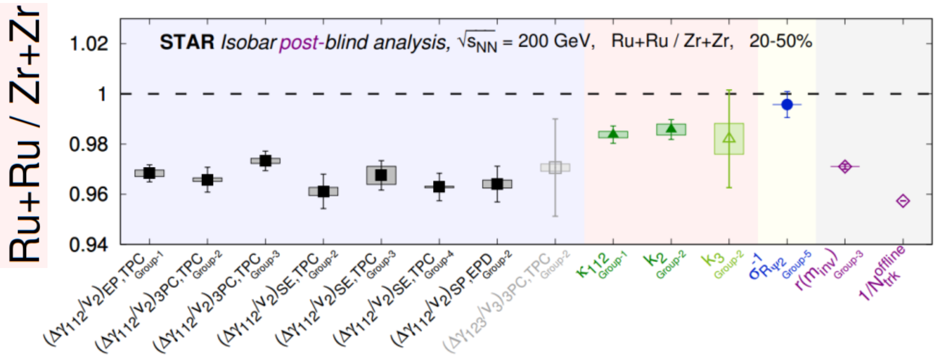


Isobar collisions at STAR

Varying the magnetic field

Idea: similar nuclei (same # of baryons), different charge

- Ruthenium generates a 10% larger magnetic field
- Ideal set-up to suppress background and detect Chiral Magnetic Effect (CME)
- Very precise blinded analysis by STAR:

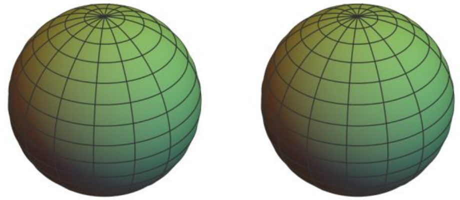


CME-like

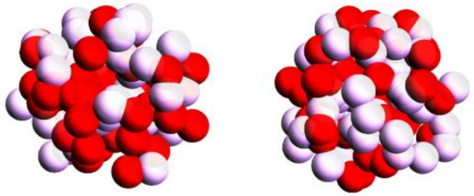
No CME

Unfortunately (?), no CME detected

$^{96}_{44}\mathrm{Ru}^{44+}$ $^{96}_{40}\mathrm{Zr}^{40+}$

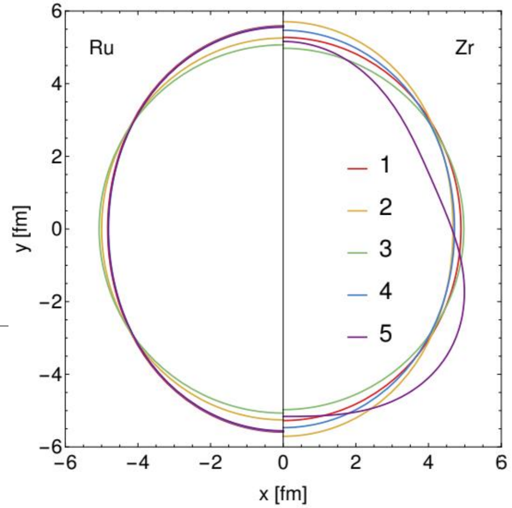


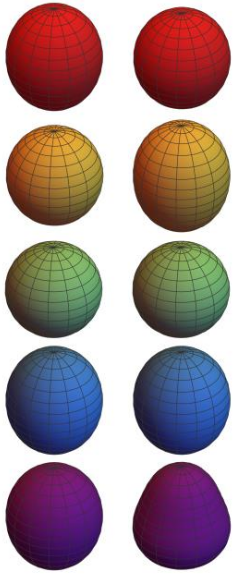
Averaged



Fluctuating (realistic)

Isobar collisions at STAR





Five different cases simulated:

nucleus	R_p [fm]	σ_p [fm]	R_n [fm]	σ_n [fm]	β_2	β_3	σ_{AA} [b]
$^{96}_{44}$Ru(1)	5.085	0.46	5.085	0.46	0.158	0	4.628
$^{96}_{40}$Zr(1)	5.02	0.46	5.02	0.46	0.08	0	4.540
$^{96}_{44}$Ru(2)	5.085	0.46	5.085	0.46	0.053	0	4.605
$^{96}_{40}$Zr(2)	5.02	0.46	5.02	0.46	0.217	0	4.579
$^{96}_{44}$Ru(3)	5.06	0.493	5.075	0.505	0	0	4.734
$^{96}_{40}$Zr(3)	4.915	0.521	5.015	0.574	0	0	4.860
$^{96}_{44}$Ru(4)	5.053	0.48	5.073	0.49	0.16	0	4.701
$^{96}_{40}$Zr(4)	4.912	0.508	5.007	0.564	0.16	0	4.829
$^{96}_{44}$Ru(5)	5.053	0.48	5.073	0.49	0.154	0	4.699
$^{96}_{40}$Zr(5)	4.912	0.508	5.007	0.564	0.062	0.202	4.871

1. e-A scattering experiments(STAR case 1)
2. Theory (finite-range liquid drop model, STAR 2)
3. DFT with neutron skin (spherical) [1]
4. DFT with neutron skin (deformed, β_2 = 0.16) [1]
5. As 4, but with β_2 from electric transition probability and β_3 from comparing AMPT with STAR [2]

[1] Hao-jie Xua, Hanlin Lib, Xiaobao Wanga, Caiwan Shena and Fuqiang Wang, Determine the neutron skin type by relativistic isobaric collisions (2021)
[2] Chunjian Zhang and Jiangyong Jia, Evidence of quadrupole and octupole deformations in 96Zr+96Zr and 96Ru+96Ru collisions at ultra-relativistic energies (2021)

Effect of viscosity on observables

Significant effects, but cancel in the ratio